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Technical design and evaluation of potential repository concepts for long-lived low and intermediate level waste

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Keywords: SFL, SFL Concept study, Concrete repository, Clay repository, Gravel repository, Super silo.

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Abstract

In Sweden there is, in addition to short-lived low and intermediate level waste and spent nuclear fuel, also long-lived low and intermediate level waste, which origins partly from the operation, modernization and decommissioning of the Swedish nuclear power plants, and partly from early research within the Swedish nuclear programmes and from medical, industrial and research activities.

The Swedish Nuclear Fuel and Waste Management Co. (SKB) plans to build a separate repository for long-lived low and intermediate level waste – SFL. Operation is scheduled to start around 2045. As part of the planning for SFL, SKB has conducted a concept study to identify and evaluate possible solutions for the final disposal of the Swedish long-lived low and intermediate level waste. The objective of the Concept study is to recommend a maximum of two disposal concepts for assessment of the long-term safety and further development.

This report describes work done within the SFL Concept study. In the initial stages of the concept study, four concepts have been identified for further analysis. The report aims to evaluate these repository concepts based on technical and economic aspects such as constructability, operation and costs:

- A repository with engineered barriers of mainly concrete – The Concrete repository.
- A repository with engineered barriers of mainly bentonite clay – The Clay repository.
- A repository that is based on a hydraulic cage around the waste – The Gravel repository.
- A repository combining multiple barriers in a silo construction – The Super silo.

All repository concepts are based on disposal in crystalline bedrock at a depth, 300–500 metres, where the repository is not exposed to freezing during future glaciations. For calculations in this study it is assumed that SFL is sited approximately 500 metres below sea level. All waste will be conditioned and packaged in custom containers before being transported to the repository.

The present study has shown that all repository concepts have their strengths and weaknesses.

The Concrete repository is similar to the cavern 1BMA in SFR and can be built with known and established technology, either as a long rock vault or in a more compact shape. Custom sizes for different parts of the repository are possible. Before closure, the repository will be backfilled with large amounts of concrete. This process is a future development area since it is necessary to control shrinkage and cracking etc.

The Clay repository can be built either as long rock vaults or in more compact shape. No clay is installed during construction of the repository. Before closure, the repository will be backfilled with large amounts of bentonite clay. The backfilling process requires further development, to ensure high enough density and high enough installation rate. The operational structures need to be developed to facilitate the backfilling process. Provided that all waste containers have been filled with concrete materials the waste matrix is expected to be stable enough to withstand the swelling clay.

The Gravel repository is the concept that would be the easiest to develop and build, and also the economically most favourable. To ensure safety during operation, the concept needs to be supplemented with barriers for radiation protection. Questions are raised regarding the risk over time of clogging of the high-permeable medium. The concept places higher demands on the long-term properties of the waste containers than the other concepts.

The Super silo is the concept that meets the greatest challenges and difficulties. The Super silo is the most complex structure and is therefore expected to require most financial resources for the development and construction of the compared concepts. It is not possible to demonstrate that a silo construction, with the proposed design and the necessary size, is technically suitable because of the groundwater pressure at the repository depth in question and the swelling pressure of the clay. Significant reduction of the silo diameter would be necessary which is unfavourable for the waste deposit volume.

In conclusion, the Clay repository and the Concrete repository are the most interesting concepts for future safety analyses, and research and development.

Sammanfattning

I Sverige finns det, utöver kortlivat låg- och medelaktivt avfall och använt kärnbränsle, även långlivat låg- och medelaktivt avfall, med ursprung dels från drift, modernisering och rivning av de svenska kärnkraftverken, dels från tidig forskning inom de svenska kärnforsknings-programmen och från sjukvård, industri och annan forskning.

Svensk Kärnbränslehantering AB (SKB) planerar att bygga ett separat slutförvar för långlivat låg- och medelaktivt avfall – SFL. Driftstarten planeras till omkring 2045. Som ett led i planeringen av SFL har SKB genomfört en konceptstudie för att identifiera och utvärdera möjliga lösningar för slutligt omhändertagande av det svenska långlivade låg- och medelaktiva avfallet. Målet med konceptstudien är att rekommendera maximalt två förvarskoncept för värdering av den långsiktiga säkerheten och vidare utveckling.

Denna rapport redovisar arbete som utförts inom projekt SFL Konceptstudie. I ett inledande steg av konceptstudien har fyra koncept identifierats för vidare analys. Syftet med rapporten är att utvärdera dessa slutförvarskoncept utifrån tekniska och ekonomiska aspekter, som byggbarhet, drift och kostnader:

- Ett förvar med huvudsaklig barriär i form av betong – Betongförvaret.
- Ett förvar med huvudsaklig barriär i form av bentonitlera – Lerförvaret.
- Ett förvar som bygger på att skapa en hydraulisk bur kring avfallet – Grusförvaret.
- Ett förvar som kombinerar flera barriärer i en silokonstruktion – Supersilon.

Samtliga förvarskoncept bygger på förläggning i kristallin berggrund på ett sådant djup, 300–500 meter, att förvaret inte utsätts för frysning i samband med framtida glaciationer. För beräkningar i den här studien förutsätts att SFL förläggs ca 500 meter under havsnivå. Avfallet kommer att konditioneras och förpackas i anpassade behållare innan det transporteras till slutförvaret.

Föreliggande studie visar att alla förvarskoncept har sina styrkor och svagheter.

Betongförvaret påminner om förvarsdelen 1BMA i SFR och kan byggas med känd och etablerad teknik, antingen som en lång bergssal eller i mer kompakt form. Anpassade storlekar för olika förvarsdelar möter inget problem. Inför förslutningen återfylls förvaret med stora mängder betong. Denna process är ett framtida utvecklingsområde eftersom man behöver kunna kontrollera krympning och sprickbildning etc.

Lerförvaret kan byggas antingen som långa bergssalar eller i mer kompakt form. Ingen lera installeras vid konstruktionen av förvaret, utan först inför förslutningen återfylls förvaret med stora mängder bentonitlera. Återfyllningsprocessen kräver vidare utveckling, för att säkra tillräckligt hög densitet och erforderlig installationshastighet. Driftkonstruktionen behöver utvecklas för att underlätta återfyllnadsprocessen. Förutsatt att alla avfallsbehållare har fyllts med betongmaterial så förväntas avfallsmatrisen vara tillräckligt stabil för att stå emot den svällande leran.

Grusförvaret är det koncept som skulle vara enklast att utveckla och bygga, och också mest ekonomiskt föredelaktigt. För att säkerställa säkerheten under drift behöver konceptet kompletteras med barriärer för strålskydd. Frågetecken finns gällande risken för igensättning över tid av det högpermeabla mediet. Konceptet ställer högre krav på avfallsbehållarnas långtidsegenskaper än de övriga koncepten.

Supersilon är det koncept som möter störst utmaningar och svårigheter. Supersilon är den mest komplexa konstruktionen och bedöms därför kräva mest ekonomiska resurser för att utveckla och bygga av de jämförda koncepten. Det är inte möjligt att visa att en silokonstruktion, med den föreslagna utformningen och den nödvändiga storleken, är byggtekniskt hållbar på grund av grundvattentrycket på aktuellt förvarsdjup och svälltrycket från leran. Kraftig reduktion av silons diameter är nödvändig för att säkra konstruktionen, vilket är ogynnsamt för deponeringsvolymen.

Sammanfattningsvis anses Lerförvaret och Betongförvaret vara de mest intressanta koncepten för kommande säkerhetsanalyser samt forskning och utveckling.

Contents

1 Introduction

The main objective of the SFL Concept study is to identify and evaluate suitable concepts for the repository for long-lived waste – SFL – and to recommend one or two of them to be further assessed with respect to long-term safety. The outcome of the assessment will determine whether the system meets the requirements on post-closure safety and may constitute SKB's main alternative for the future development and planning of SFL. The repository is planned to be commissioned in 2045.

As a part of the SFL Concept study, a number of possible repository concepts were identified for SFL. Following the primary assessment the number was reduced to the four following concepts, which are covered by this report:

- The Concrete repository.
- The Clay repository.
- The Gravel repository.
- The Super silo.

The details of the SFL Concept study, including objectives, scope, methodology, and conclusions, are reported in Elfwing at el. (2013).

1.1 Scope of this study

The purpose of this report is to compile the technical studies that have been undertaken to explore the proposed concepts and to evaluate them as a possible final disposal concept for SFL. Finally, recommendations are given for future work of the SFL repository, from a technical design point of view.

An important limitation of this report is that the four designated repository concepts are studied on an overall technical basis, each one separately, and possible refinements or combinations of the concepts are discussed only to a minor extent. Aspects of long-term safety, as well as environmental aspects, are not covered by this report.

The location of the SFL site is handled entirely unprejudiced, except that it is assumed to be a geological disposal at a depth where the barriers will not suffer from freezing during future glaciations, i.e. at least 300 metres down into the Swedish crystalline bedrock. For this study a repository depth of 500 metres has been assumed.

1.2 Objectives

The objectives of the work presented in this report are to identify strengths and weaknesses among the four repository concepts treated in this study. This work will then form a basis for the final evaluation of the concepts which is presented in the SFL concept study main report by Elfwing et al. (2013).

The main focus in this study is on technical aspects such as feasibility of the design and construction of the different repository concepts and feasibility of technology and method of operation. Also covered are aspects related to personal safety, working environment, and cost.

1.3 Outline of the report

The structure of this report is as follows:

- Chapter 2 gives a brief background to SKB's plans for the repository and describes superficially the management and amounts of long-lived low and intermediate level waste.
- In Chapter 3 the methodology which has been used for this work is described together with the evaluation process for selecting the most feasible repository concepts.
- In Chapter 4 the evaluation factors are specified for the evaluation categories "Technology" and "Cost and time".
- In Chapter 5 the prerequisites for this study are given.
- In Chapter 6 a general description of the repository and repository facilities is given, including the construction phase.
- Chapters 7–10 describe the four selected repository concepts included in the study, each one in a separate chapter. Furthermore, the technical studies undertaken and associated results are presented here.
- In Chapter 11 the operation and maintenance aspects of the repository are discussed.
- In Chapter 12 backfill, sealing and closure of the repository are discussed.
- Chapter 13 presents the evaluation of the repository concepts, using the identified evaluation factors.
- In Chapters 14 and 15 conclusions and recommendations for future work are presented.

1.4 The project team

The work presented in this report, has been carried out by Pär Grahm, David Luterkort, Per Mårtensson, Fredrik Nilsson and Björn Nyblad at SKB together with Bojan Stojanovic and Mikael Oxfall, Vattenfall Research & Development.

1.5 Terms and abbreviations

Below, terms and abbreviations used in this report are explained:

Term or abbreviation	Description
ATB	Radiation-shielded transport cask for intermediate level waste.
Backfilling	Backfilling refers to the process of filling the disposal caverns holding the RWCs with a specific material. The process is undertaken when the disposal of RWCs in the cavern has been finalized. Concrete, clay or gravel can be used as backfill material. The design differs between the studied concepts in this report.
BMA	Rock cavern for intermediate level waste in SFR.
BWR	Boiling water reactor.
Closure	Closure refers to the filling of transport tunnels, shafts and the surface entrance to SFL. This action will further reduce the groundwater flow through the caverns and prevent access to the tunnels.
LL-LILW	Long-lived low and intermediate level waste.
NPP	Nuclear power plant. The Swedish NPPs are: Oskarshamn (O1, O2, O3), Forsmark (F1, F2, F3), Ringhals (R1, R2, R3, R4) and Barsebäck (B1, B2; both closed).
PWR	Pressurized water reactor.
RWC	Repository Waste Container enclosing the LL-LILW. The waste is stabilized with grout in the RWC prior to disposal. The RWCs are free from surface contamination.
Sealing	Sealing refers to construction of a section with low hydraulic conductivity at the tunnels adjacent to the caverns. This sealing will minimise the axial flow of groundwater through the cavern access tunnels.
SFL	Repository for long-lived radioactive waste.
SFR	Repository for short-lived radioactive waste. Located in Forsmark and operated by SKB.

2 Background

The development of a barrier system for SFL requires detailed knowledge about the waste categories to be disposed of in the repository and also a strategy for handling and conditioning of the waste. Furthermore, inputs from previous safety assessments and other related projects – such as the SFR extension project and the Spent Fuel Repository – are important.

In Section 2.1 a brief summary of the waste categories that will be disposed of in SFL and the work with the updating of the reference inventory will be presented.

In Section 2.2 a summary of the first pre-study and the preliminary safety assessments for SFL, presented in 1995 and 1999 respectively, is presented together with the most important conclusions.

2.1 Reference inventory

Long-lived low and intermediate level waste planned for disposal in SFL comprises four main categories:

- Neutron-irradiated components such as reactor internals, core components and PWR pressure vessels from maintenance and decommissioning of the Swedish nuclear power plants.
- BWR control rods from operation of the Swedish nuclear power plants.
- Waste from early research in the Swedish nuclear programmes (currently managed by AB SVAFO).
- Waste from other sources such as industries, hospitals and research facilities including waste from operations in Studsvik.

A reference inventory for SFL was compiled in 1998 (SKBdoc 1416968) and used in the preliminary safety assessment for SFL3–5 (SKB 1999). This reference inventory was based on the then-current plans regarding operation and closure of the NPPs. The plans have since then been revised.

This section is based on the updated SFL reference inventory of waste from the nuclear power plants (Herschend 2013), the RD&D programme (SKB 2013), and on figures provided by AB SVAFO and Studsvik Nuclear AB to serve as basis for the updated reference inventory.

An estimated timetable for when the waste for SFL will be produced and the corresponding estimated repository volume required is presented in Figure 2-1.

From Figure 2-1, it is recognized that the total amount of waste for SFL is limited to about 16,000 m^3, which makes SFL the smallest repository of the planned three repositories for nuclear waste in Sweden. Also, it is recognized that a significant fraction of the waste planned for SFL already exists, as shown by the purple line “accumulated volume”. The existing waste volume is mainly waste from early research in the Swedish nuclear programmes (legacy waste).

Below, some more information about the different waste categories is presented.

2.1.1 Waste from the Swedish nuclear power plants

The waste from the nuclear power plants comprises components with a significant content of long-lived radioactive isotopes. These components are typically located close to the core itself, where the neutron flux creates induced activity in the component material. The elevated levels of long-lived nuclides make the core components unsuitable for disposal in SFR.

The core components from the BWRs include the core support structure (moderator tank, moderator tank cover, core grid and the upper part of the control rod guide tubes) and the core spray. Also included are control rods, neutron detectors, guide tubes, boron plates and fuel boxes (including spacers etc). No steam separators have been included in the summary, since they are planned for disposal in SFR.

The waste from the PWRs includes all reactor internals and the entire reactor pressure vessel.

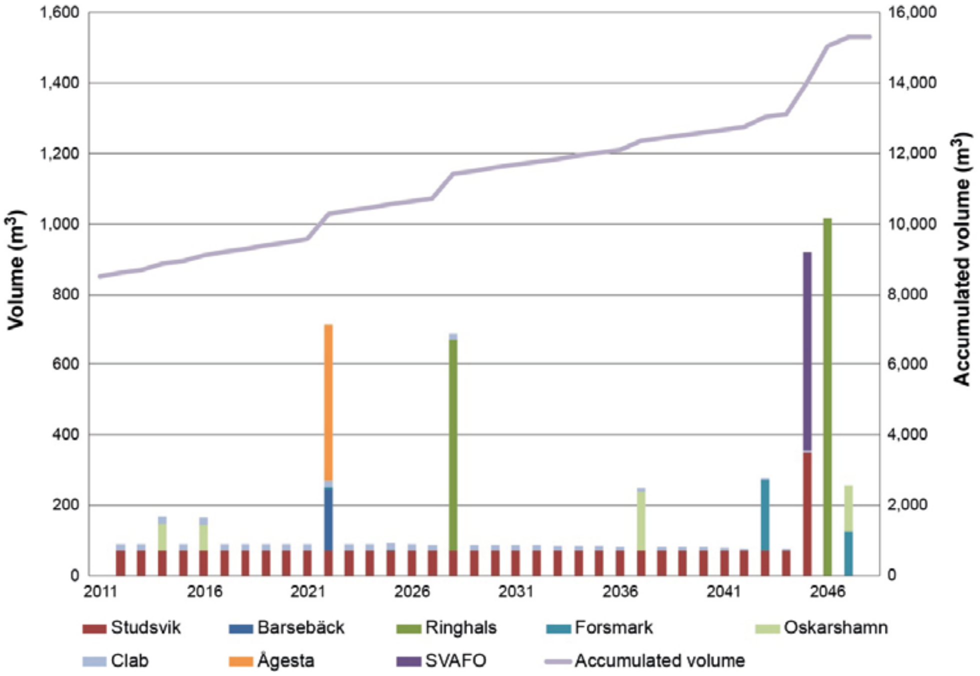


Figure 2-1. *An estimated timetable for when the waste for SFL will be produced and the corresponding estimated repository volume required (SKB 2013).*

The waste from operation and maintenance of the nuclear power plants is currently stored in pools at the sites of the nuclear power plants or at the Central storage for spent nuclear fuel (Clab), but also in steel tanks under dry conditions. This waste has not yet been conditioned for disposal and can thus be retrieved.

The total activity of the waste from the Swedish nuclear power plants is estimated to be $2.1 \cdot 10^{17}$ Bq in 2075 (Herschend 2013). The estimated disposal volume of waste from the Swedish nuclear power plants is slightly less than 5,000 m^3.

2.1.2 Waste from SVAFO and Studsvik Nuclear

This waste category mainly consists of legacy waste from early research in the Swedish nuclear programmes (currently managed by AB SVAFO), and waste from other sources such as industry, hospitals and research facilities (currently managed by Studsvik Nuclear AB). Figures provided by AB SVAFO and Studsvik Nuclear AB to serve as bases for the updated reference inventory are presented in this section. It should be noted that there are large uncertainties regarding the content of the waste, mainly related to the scarce documentation of the legacy waste and to the forecasted operational waste from Studsvik Nuclear AB.

This section is divided into three parts: legacy waste, existing operational waste, and future operational and decommissioning waste.

Legacy waste

Legacy waste comprises long-lived low and intermediate level waste that was produced during the development of the Swedish nuclear programmes in the 1960s and early 1970s and is stored today at the Studsvik site. Large parts of the waste are stored in drums filled with a mixture of waste and grout. By the time of conditioning, the waste was considered to have limited radiotoxicity and documentation of the waste is thus scarce.

Figures provided by AB SVAFO and Studsvik Nuclear AB to serve as basis for the updated reference inventory show that about 7,300 m^3 of legacy waste is stored at the Studsvik site today, with an estimated total activity of $1.0 \cdot 10^{15}$ Bq is 2075.

Existing operational waste

The waste from Swedish industry, hospitals, universities and research facilities is handled by Studsvik Nuclear AB, which prepares the waste for disposal and store it until a repository is available. AB SVAFO and Studsvik Nuclear AB has currently about 350 m^3 of operational waste planned for disposal in SFL in storage. This waste is mainly stored in 200-litre drums at the Studsvik site. The total activity content of the existing operational waste is estimated to $1.3 \cdot 10^{12}$ Bq.

Future operational waste and decommissioning waste

Future operational waste (until 2045) and waste from the dismantling of the facilities in Studsvik will render approximately 3,300 m^3 of waste planned for SFL. There is currently no information on the forecasted activity of this waste fraction.

2.2 Previous studies for SFL

Preliminary design studies and safety assessments for SFL have been previously undertaken and they were reported in 1995 (Wiborgh 1995) and 1999 (SKB 1999), respectively. The assessment in 1995 was mainly considered as a pre-study to the 1999 safety assessment and will not be further discussed here.

2.2.1 Design of engineered barriers and waste containers

The repository concept evaluated in SKB (1999) comprised concrete structures placed in crystalline bedrock at about 300 metres depth. Two rock caverns were planned: SFL 3 (for legacy waste from the development of the Swedish nuclear programmes and operational waste from the central storage facility for spent nuclear fuel (Clab) and the Encapsulation Plant) and SFL 5 (for the neutron-irradiated components from the nuclear power plants). The short-lived decommissioning waste from Clab and the Encapsulation Plant was planned to be emplaced in the transport tunnels (SFL 4).

SFL 3 and SFL 5 contained an engineered concrete barrier and the design resembled that of the rock cavern for intermediate level waste, BMA, in SFR, Figure 2-2 (left image). SFL 4 comprised a simple tunnel design with no engineered barriers, a design similar to the rock cavern for low-level waste, BLA, in SFR, Figure 2-2 (right image).

Four types of waste containers were planned to be used for the LL-LILW in SFL 3 and SFL 5. Waste from Clab and Studsvik would mainly be placed in standard moulds with the dimensions 1.2 × 1.2 × 1.2 m^3 or in standard 200-litre drums, whereas the more active waste should be placed in small drums which then were placed in shielded concrete moulds. In SFL 4 mainly standard ISO containers were planned to be used.

Figure 2-2. *The rock cavern for intermediate level waste, BMA, in SFR (left) and the rock cavern for low-level waste, BLA, in SFR (right).*

2.2.2 Conclusions from the preliminary safety assessment

The repository's ability to restrict the release of radionuclides was evaluated for three different sites with different characteristics.

The safety assessment showed that the suggested repository concept was sensitive to the properties of the site such as groundwater flow at repository depth and the ecosystem on the ground surface. In SKB (1999) the following was concluded:

"The safety assessment shows how important the site is for the safety. Two factors stand out as being particularly important: the water flow at the depth in the rock where the repository is built, and the ecosystem in the areas on the ground surface where releases may take place in the future. Another conclusion is that radio nuclides that are highly mobile and long-lived, such as Cl-36 and Mo-93 are important to take into consideration. Their being long-lived means that barriers and the ecosystems must be regarded with a very long time horizon."

In their review the authorities (Swedish Radiation Protection Institute, SSI, and Swedish Nuclear Power Inspectorate, SKI) shared SKB's conclusion that there is a significant site-specific impact on the long-term safety. SKI and SSI called for a repository design that can be considered sufficiently robust with respect to the influence of site-specific factors and their long-term evolution (SKI and SSI 2001).

3 Methodology and evaluation process

As mentioned in the introduction to this report, the main objective of the SFL Concept study is to provide a recommendation of one or two repository concepts for the LL-LILW which will be further analysed over the coming years in an evaluation of the long-term safety. The methodology is described in detail in the SFL Concept study main report by Elfwing et al. (2013).

The method used is intended to achieve transparency and traceability in the evaluation process. The principle for the methodology is that all initially identified concepts are evaluated against the identified relevant requirements. A concept that can be shown not to fulfil requirements or to have serious drawbacks compared with other concepts in terms of the requirements will be excluded from further evaluation.

Based on the requirements, evaluation factors are formulated. To ensure a traceable evaluation process, each requirement is connected to at least one evaluation factor. As a result, requirements can be used for the evaluation of the concepts, via the evaluation factors. These evaluation factors are grouped into evaluation categories. The evaluation factors for this report, concerning evaluation categories "Technology" and "Cost and time", are listed in Chapter 4.

The following four repository concepts were identified for further studies by Elfwing et al. (2013) and are treated in this report:

- The Concrete repository.
- The Clay repository.
- The Gravel repository.
- The Super silo.

3.1 Refinement of the nominated concepts

Prior to the evaluation based on evaluation categories "Technology" and "Cost and time", these concepts were slightly adjusted in order to make the judgements more correct and fair. Typically, this mainly concerned the layout and dimensions of the engineered barrier systems. The refined design of each nominated repository concept is described initially in the respective Chapter 7 to 10.

3.2 Evaluation based on Technology and Cost and time

The objective of the studies presented in this report is to evaluate the technological and cost-and-time aspects of the nominated four concepts listed above. The evaluation factors with detailed criteria are listed in Chapter 4.

Chapters 7 to 10 give a comprehensive analysis of relevant design issues to ascertain the strengths and weaknesses of each repository concept for the future SFL.

The outcome of the evaluation is presented in Chapter 13. The conclusions are summarized and presented in Chapter 14 while future activities are discussed in Chapter 15. In all, this becomes the basis for the future research program on engineered barrier systems being presented in SKB (2013) and Elfwing et al. (2013).

4 Evaluation categories

The evaluation categories of the SFL Concept study are illustrated in Figure 4-1. This report covers merely evaluation of the categories "Technology" and "Cost and time" whereas the evaluation of the long-term safety and the evaluation of environmental aspects etc are described in Elfwing et al. (2013).

4.1 Technology

Below, the defined evaluation factors within the category "Technology" are described together with their associated detailed criteria.

4.1.1 Personal safety and working environment

- Safety at work.
  - Risk of accidents during construction and operation, emergency conditions, possibility to prevent accidents.
- Likelihood and consequence of an accident leading to release of radioactive substances.
  - In the event of an accident, this shall not lead to an unacceptable release of radionuclides from the package.
- Need for radiation protection and expected dose to staff and visitors.
- Ability to provide good working environment.

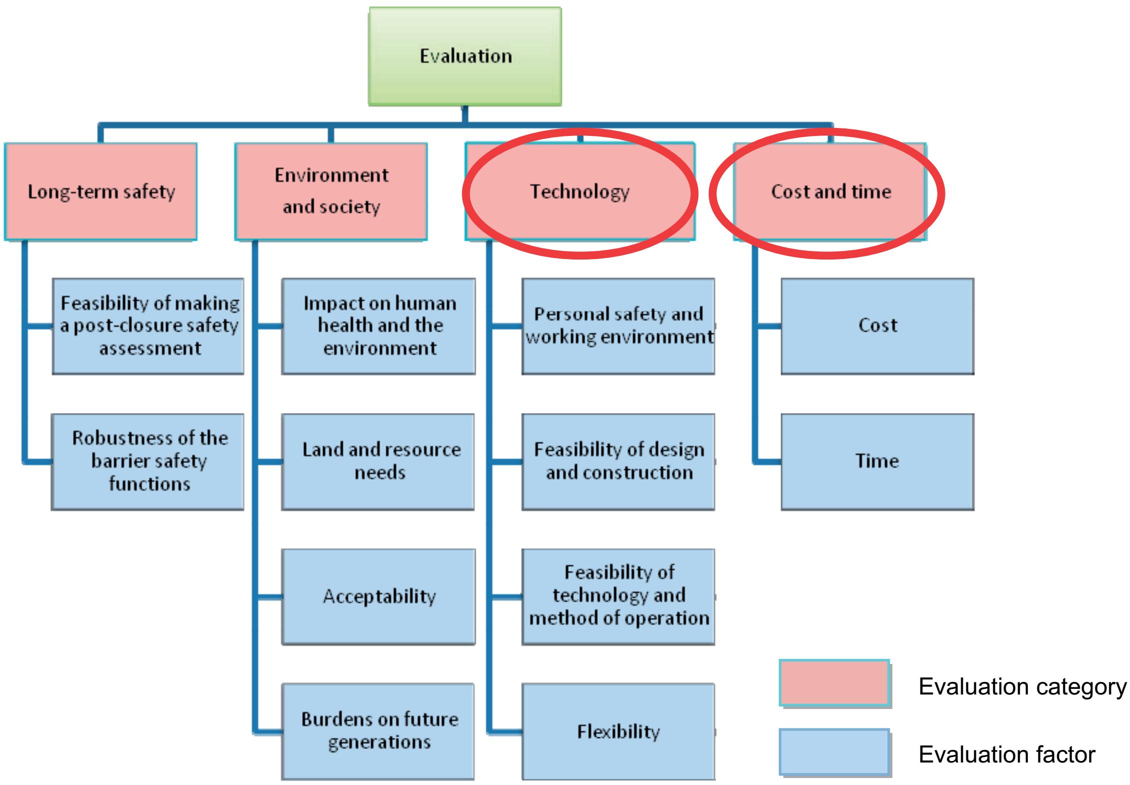


Figure 4-1. *Illustration of the evaluation categories and evaluation factors used in the SFL Concept study.*

4.1.2 Feasibility of design and construction

- Technical maturity.
  - To what extent is the concept developed (known technology, partly known technology, unknown technology)?
- Simplicity in design and construction.
  - Difficulty to build (constructing):
    - Manufacturing and installation of engineered barriers.
    - Technology for rock engineering: preparation methods, rock reinforcement, drilling, blasting, impacts on natural and engineered barriers, water diversion.
    - Backfilling and Closure.
- Resistance during the operating period.
  - The design's resistance during the operational period (to reach the initial state, package, barriers):
    - Chemically resistant.
    - Mechanically resistant.
    - Robustness.
    - The waste packages' content of radionuclides should not cause the internal dose rate or integrated dose of radiation to have unacceptable impacts on the package.
    - The waste packages' mechanical strength shall be sufficient so that anticipated load cases do not cause damage leading to release of radioactive substances.
- Feasibility of quality control and maintenance (of construction).
  - Is it possible to correct deficiencies in safety or impact on the initial conditions?
- Feasibility of physical protection (plant design).
- Possibility for safeguard (plant design).

4.1.3 Feasibility of technology and method of operation

- Maturity in technology.
  - To what extent is the concept developed (known technology, partly known technology, unknown technology)?
  - Identify the major needs of research and development.
- Easiness in method (Includes assessment of how difficult, complex deposition and handling, conditioning of the waste package is).
  - What are the problems and risks with the chosen method of operation?
  - Simplicity to reach the initial state (not adversely affect the barriers, etc).
- Safety during operation (reliability, possibility to correct in case of accident, robustness for unforeseen events).
- The possibility of quality control (of deposition, conditioning, etc).
  - Is it possible to correct deficiencies in safety or impact on the initial conditions?

4.1.4 Flexibility

- Flexibility in technology and method of operation.
  - Adapting to changing volumes, waste types, packaging, access to different modes of transport, adaptation to the waste that is physically, chemically or radiologically difficult to handle.
- Flexibility in design and construction.
  - Flexibility in layout, the ability to build in stages, adjusting the design to changing volumes, waste types, packaging, adaptation to different geological environments. Adaptation to waste which is physical, chemical or radiological difficult to handle.

4.2 Cost and time

Below, the defined evaluation factors within the category "Cost and time" are described together with their associated detailed criteria.

4.2.1 Cost

The cost for the project includes:

- Investment.
  - Rock excavation.
  - Consumption of material.
  - Energy consumption.
  - Infrastructure (machinery, equipment, media, safety systems, above-ground facilities)
- Operation and maintenance (including decommissioning and closure).
  - Energy consumption.
  - Staff.
  - Maintenance.
  - Supplies.
  - Availability.
- Research & Development.

4.2.2 Time

- Likelihood that the program can be implemented in accordance with the time schedule.

5 Prerequisites for the study

This chapter presents the prerequisites and conditions for the study. This includes general conditions as well as assumptions made regarding waste containers and the handling and disposal of waste containers in SFL.

5.1 General conditions

The following general conditions apply for this study:

- The study is limited to evaluate the four nominated repository concepts (see Chapter 3).
- The scope is to investigate the conceptual designs as far as necessary to allow comparison between the nominated concepts using the evaluation factors.
- All four nominated concepts are based on the location in crystalline rock at a depth of 300–500 metres. For studies in this report, a depth of 500 metres is used as a basis for all assessments made. This implies that the engineered barrier system must withstand a hydrostatic pressure from the groundwater of approximately 5 MPa.
- Geologically stable conditions are expected and the impact of earthquakes is not considered in the comparison between the concepts.
- The content of long-lived radionuclides in SFL implies that the barriers and the ecosystems must be regarded on a very long timescale. In the case of a repository for long-lived waste, the safety assessment should at least cover approximately one hundred thousand years or the period for a glacial cycle. For the time following one hundred thousand years, the safety assessment needs to show the safety of the repository in a more qualitative way, for a maximum time period of up to one million years.
- The total volume of LL-LILW to be deposited is estimated to about 16,000 m^3 (Section 2.1). Possibilities for the repository to handle a future increase of the amounts of waste will be evaluated.
- The repository facility will consist of surface facilities and underground facilities connected by a shaft and a ramp. In this report it is assumed that the ramp is used for transports of waste transport containers and backfill material for the underground part.
- To put focus on the design and construction of the engineered barriers of the repository, no long-term safety function is assigned to the waste container or the waste.
- Since focus of the evaluation is set on the design and construction of the engineered barriers in the disposal area, common parts of the repository (like transport tunnels, spaces for ventilation, electricity and storages etc) are not as important to compare while they are similar for all concepts.
- Future design and construction of the repository will consider the interaction between humans, technology and organisation (MTO). These aspects are not separately studied at this early stage.

5.2 Waste containers

A prerequisite for this study is that the waste to be deposited in SFL will be packaged and handled in the following waste containers:

5.2.1 Waste containers for the legacy waste

The legacy waste is proposed to be placed in steel overpacks as shown in Figure 5-1 (Pettersson 2013). The design facilitates the use of grout to stabilise the original waste containers – moulds and drums – prior to transport and also to reduce the void volume in the repository. This procedure is motivated by the need for an efficient transport and handling system.

5.2.2 Waste container for the NPP waste

Core components are today stored in pools either at the NPPs sites or in the central storage for spent fuel (Clab). Some of the core components are also stored under dry conditions in steel tanks.

Two handling alternatives are identified in Pettersson (2013):

1. To use steel tanks, currently used for storage, also for disposal. In addition, future waste from the NPPs can be placed in corresponding steel tanks. This is beneficial since no waste would require repacking, but also since there is today a handling system based on these tanks in operation at the NPPs. In the case that the waste from the NPPs are placed in a separate rock vault there is no benefit in using a container with the same dimensions as the ones for the legacy waste and the steel tank is therefore a good option.
2. To tranship core components into steel containers, which have the same external dimensions as the containers for the legacy waste, Figure 5-2. However, the type and thickness of the material in the containers can be varied to suit the requirements from the different waste categories. This option renders a uniform container size for all types of waste which is beneficial in the waste management. The drawback is that all waste today stored in steel tanks would require repacking.

For further details about the containers, see Pettersson (2013).

Figure 5-1. *Waste containers for the legacy waste currently stored in moulds and drums.*

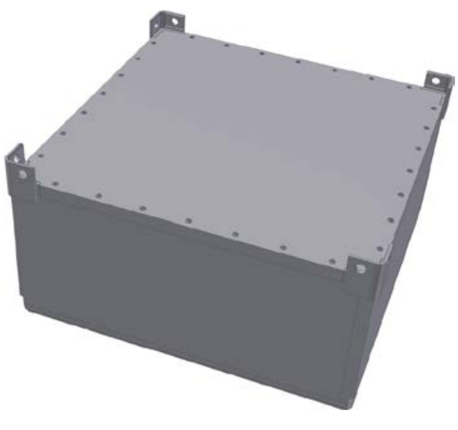


Figure 5-2. *Shielded waste container for core components. The external dimensions are the same as for the containers for the legacy waste but the thickness of the steel can be adjusted to comply with the requirements set by the level of radiation from the waste.*

5.2.3 Handling of PWR pressure vessels

In this study it is assumed that the PWR pressure vessels are to be segmented and packed into shielded waste containers prior to disposal. This should not be seen as a decision on the details of the repository or the handling of the waste, but rather a choice to allow for straightforward comparison between repository concepts.

A detailed analysis of the entire handling chain for the PWR pressure vessels needs to be conducted to investigate the technical possibilities for the handling and disposal of whole tanks, and highlight the consequences in all steps in terms of dose to personnel and cost. Handling of whole PWR pressure vessels will for example affect the layout of ramp and main tunnels, and the vessels may also need a separate cavern.

5.3 Handling and disposal of the waste

In this section, the assumptions made regarding the handling and disposal of waste containers in SFL are presented.

5.3.1 Transportation

The waste handling system for the LL-LILW must be adapted to SKB's present transport and handling system and appropriate radiation shielding must be provided during handling, transportation and storage.

To enable transportation, waste transport containers (ATBs) and repository waste containers (RWCs) will be uniformly designed. This is a generic issue independent of repository concept.

5.3.2 Storage

For waste that emerges prior to the the starting of operations in SFL, a facility for storage will be required. The size of this storage is dependent on the time when SFL is taken into operation but also on when the waste is packed into containers. This issue is not further treated in this report.

ATBs, with RWCs inside, will be possible to store temporarily in the surface part of the repository facility before being transported to the underground part. Storage space for ATBs on surface will correspond in capacity to the deliveries from the waste producers and allow for continuous deposition pace.

5.3.3 Disposal

At the time for disposal, the loaded ATB will be transported to the underground part via the ramp.

Unloading of RWCs from the ATB is done in the underground part in connection to the disposal area.

Deposition is performed in open vaults according to the SFR-model (open rock caverns like 1BMA or Silo) that are later on backfilled with barrier material and sealed.

The deposition process, i.e. transport to underground via the ramp, emptying of the transport container and disposal of RWCs in a pre-defined position, is assumed to be as automated as possible. The entire process and all essential repository systems will be possible to monitor and control from an operation central.

No free activity is expected in either air or water in the repository. Natural background radiation, natural amounts of radon and radon progenies can occur in the underground part. Equipment that detects contaminated surfaces on the inside of the ATB and on the RWCs will be available.

6 General description of the repository and the repository facilities

The SFL repository and repository facilities comprise several parts which are of importance for the overall function. As given by the introduction, the four following repository concepts are studied in this report.

- The Concrete repository.
- The Clay repository.
- The Gravel repository.
- The Super silo.

The evaluation of the concepts focuses on the underground part and the engineered barrier systems (i.e. the disposal area) since the SFL repository facilities are considered to be of mainly generic design. In other words, each concept means a specific design solution for the disposal area of the LL-LILW.

The technical characteristics, design principles and installation challenges for each one of the four repository concepts (disposal areas) are described in the Chapters 7–10.

In this chapter, the SFL repository and repository facilities are described together with their life-cycle phases and the construction principles of the facility.

6.1 The repository facility

SFL will be divided into blocks based on whether or not handling of radioactive substances is performed. Parts of the repository where nuclear waste is handled constitute their own block which is designated a strong physical protection, i.e. secured area.

The other parts of the repository constitute a separate block. The blocks are given unique numbers and designations in accordance with SKB's other facilities (e.g. SFR, SFK). As a suggestion the SFL-blocks can be labelled:

- Block 11, SFL Nuclear facility
- Block 12, SFL Outer facility

A list detailing the systems included in the repository will be compiled during the design phase. Numbering in the system list will be based on the same division (main groups 1–9) as used commonly by the Swedish nuclear industry. For clarity, a system will be stated a three-digit system number with the block number as prefix, e.g. 11-XYZ.

6.1.1 Surface facilities

The surface facilities of the SFL-repository will be divided into an inner and an outer operational area.

Outer operational area

The outer operational area houses buildings intended for operational functions, service and maintenance as well as for staff. No nuclear activity is conducted here thus the area is designed as a conventional gated industrial area. However, practical circumstances can allow parts of the outer operational area to have the same level of security and restrictions regarding physical protection as the inner operational area.

Inner operational area

The inner operational area consists of buildings with functions for nuclear activities. It also houses buildings with access roads and shafts to the repository's underground part. The area is classified as secured area with specific requirements on controlled entrance and area protection.

Additional areas

Outside of the operational areas, the surface part of the repository can also include information building, rock mass cache, purifying plant for water and sewage, roads, parking spaces etc.

6.1.2 Underground facilities

The underground part is defined as a nuclear facility and is completely integrated with the inner operational area above ground. The underground part of the facility consists of a central area and a disposal area connected to the surface part with ramp, elevator and ventilation shafts. The central area contains vaults with functions for the operation of the underground part. The disposal area houses the LL-LILW contained in RWCs.

Central area with connections

The central area is preferably located right beneath the operational area in the surface part of the repository. It consists of a few rock vaults with the necessary functions for the operation of the underground part. The rock vaults are connected through tunnels and arranged to always provide two emergency exit routes from each rock vault.

Disposal area

The area for disposal of the RWCs consists of a few separate rock vaults connected through tunnels. The disposal area layout will be designed based on the results from the site investigations and knowledge about all future activities to be performed. The disposal area will be dimensioned for the total number of RWCs to be deposited.

6.2 Repository phases

The phases of the repository, from construction to closure, are given by the permits required from the authorities to complete them. Before the repository is constructed, site investigations are performed aiming to survey the suitability of the site, mainly from a geological perspective.

When an appropriate site has been selected the site investigations are finalised through submitting an application to the authorities for construction and possession of the repository. When permits have been granted, construction can begin. The construction phase is finalised through submitting an application for taking the repository into operation. During the operational phase, which can be divided into test operation and routine operation, the LL-LILW is deposited. The operational phase is further described in Chapter 11.

As the deposition is finalised, decommissioning of the repository is initiated, starting with radioactive clearance of the inner operational area and thereafter backfill, sealing and closure of the underground parts. The sealing and closure phase is further described in Chapter 12.

6.3 Construction of the repository and the repository facilities

Construction of the SFL repository, located at a depth of 500 metres, is estimated to take approximately seven years. During the early stage of the construction, mainly rock work is carried out, while the majority of the buildings in the operational area are constructed during the later stage. In parallel with construction of on-ground facilities, the rock excavation will continue and be finalised.

6.3.1 Activities year 1–3

Work on ground and roads

- Roads and connections for utilities are prepared.
- Construction area is established and area for sheds, stores and parking are prepared.
- Ground and spaces in the operational area are filled and levelled.
- Rock mass cache is established in the vicinity of the operational area.
- Temporary sedimentation equipment and cleaning plant for drainage water are constructed.

Construction work

- Work sheds and temporary buildings for rock work are prepared.
- Ramp entry building, geology building and information building etc are constructed.

Rock work

- Investigations of the rock are conducted (core drilling, mapping, analysis of results and rock mechanical analysis).
- The ramp is excavated to a depth of 300 m (approximately 3 km long).
- Connections from ramp to shaft are excavated, 100 m depth.
- Parts of elevator and ventilation shafts are raise bored.

6.3.2 Activities year 4–5

Work on ground and roads

- Remaining grounds in the outer operational area are filled and levelled.
- Permanent sedimentation equipment and cleaning plant for drainage water are constructed.

Construction work

- Elevator building and ventilation building are constructed.
- Construction of entry station, administrations building etc is initiated.

Rock work

- The excavation of the ramp is completed down to the central area level.
- Construction of tunnels from ramp/central area to disposal area is initiated.
- Elevator- and ventilation shafts are further constructed.

6.3.3 Activities year 6–7

Work on ground and roads

- Physical protection around and inside the repository is completed
- Roads and plans are completed.

Construction work

- All buildings in the repository area are completed.

Rock work

- Remaining halls in the central area are blasted and completed.
- Elevator- and ventilations shafts are completed.
- Tunnels from the central area to disposal area are completed.
- Rock vaults for disposal of waste are completed.

Initiating operation

- All systems are installed and taken into operation.
- Integration tests are completed.
- Test operation is initiated.

6.4 Rock excavation

During the construction of the repository, excavated rock mass will be transported to the surface by vehicle via the ramp. The estimated excavated rock volume for the general parts of the repository, including 15% rock outside of the theoretical tunnel contour, is approximately 300,000 m^3. This does not include excavated volumes for rock vaults in the disposal area.

The excavated rock volume for the disposal area, represented by a repository concept described in Chapters 7–10, is estimated to be approximately 50,000 m^3. That corresponds to one-seventh of the total rock excavation volume for SFL.

The estimation of excavated rock mass is at this stage a rough figure. However, the needed volume is partly based on the actual design (so called "Layout D") of the Spent Fuel Repository (SFK) in Forsmark. Dimensions with respect to ramp and elevator shaft can be assumed to be equivalent between the two facilities SFK and SFL. Differences however exist for the ventilation shaft and sizes of the rock vaults in the central area as the work in SFL are judged to be of lower intensity than the work in SFK and not as demanding in terms of space.

7 The Concrete repository

In this chapter the conceptual design of the Concrete repository and the intended functions of the barrier are first described (Section 7.1). This is followed by identification of the processes which may affect the barrier properties during the construction, operation, backfilling and sealing, and post-closure phases (Section 7.2). In Sections 7.3–7.5 measures to prevent or reduce these effects are discussed.

7.1 General description of the Concrete repository

The concrete repository is a geological disposal concept in which large amounts of concrete and other cementitious materials are used in the engineered barrier system thus producing a low permeability matrix with diffusion as the main transport mechanism for the release of radio nuclides. The primary safety function of this concept is retardation. This is achieved by limiting the flow of groundwater through the waste and further by limiting the diffusive transport of substances to and from the waste.

The rock cavern will have a width of approximately 20 metres and height of about 17 metres. An illustration of the cross section of the repository is shown in Figure 7-1. The length of the cavern and the number of caverns is dependent on the total waste volume and will be decided at a later stage.

A concrete structure similar to that in the rock vault for intermediate level waste, 1BMA, in SFR, Figure 2-2, constitutes the main component of the engineered barrier system and provides radiation shielding during the operational period. The concrete structure will most likely be divided into separate compartments as in the existing 1BMA.

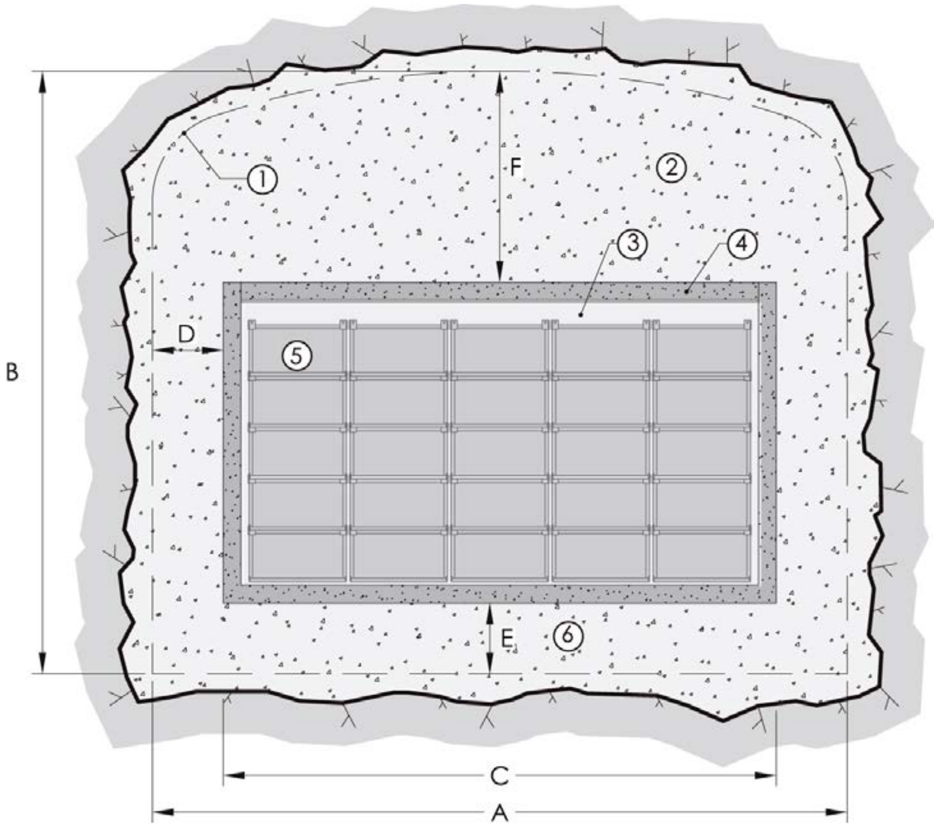
The dimensions of each compartment as well as the thickness of the walls of the concrete structure has yet to be decided but a reasonable assumption is that it will be similar to that in 1BMA, i.e. lateral dimensions of approximately 10 metres × 15 metres and a height of about 8 metres with a thickness of the outside walls of about 0.5 metre.

When the waste containers have been placed in the concrete repository the space between the containers will be filled with a grout in order to stabilize the container stack and reduce the void volume in the repository. In addition the grout will stabilize the containers and improve the strength of the entire repository by reducing the deformations due to external forces on the walls, bottom slab and lid. The grout also passivates the steel components in the waste containers due to the high alkalinity and thereby reduces the corrosion rate.

7.1.1 Main components of the engineered barrier system

The main components of the engineered barrier system are summarised below and also shown in Figure 7-1.

- The repository structure is made of reinforced concrete with a thickness of approximately 0.5 metre.
- The space above the concrete structure is filled with concrete, thickness 5–10 metres.
- The space between the concrete structure and the rock wall is filled with concrete, thickness 2 metres.
- The space between the containers inside the concrete structure is filled with concrete or grout.
- The space below the repository structure is filled with concrete, thickness 2 metres.



Figur 7-1. Cross-sectional view of the Concrete repository. Legend: 1) Theoretical tunnel contour. 2) Concrete. 3) Grout. 4) Reinforced concrete structure (0.5 m). 5) Waste containers. 6) Concrete. Approximate dimensions: A = 20 m, B = 17 m, C = 16 m, D = 2 m, E = 2 m, F = 5–10 m.

7.1.2 Safety functions of the engineered barrier system

The safety functions of the Concrete repository are:

- Low hydraulic conductivity in the concrete.
- Low diffusivity of radionuclides through the concrete.
- Strong sorption of radionuclides in the concrete.
- High-pH conditions provided by the concrete.

No safety function is assigned to the waste or containers.

7.2 Design considerations

7.2.1 Processes that may affect the engineered barrier system, overview

As mentioned in the preceding section, the main safety functions of the concrete barrier is to limit the advective flow of water and the diffusive transport of radionuclides through the barrier, and to provide a favourable chemical environment. However, during operation, backfill and sealing as well as during the post-closure period, different processes may alter the chemical and mechanical properties of the materials in the engineered barrier system and as a consequence, also the retention properties of the engineered barriers may be altered. In Sections 7.2.2–7.2.5 the most important processes are discussed.

7.2.2 Processes that may affect the engineered barrier system during the construction phase

The construction phase comprises the period prior to that the repository is taken into operation and the most important activity during this period is casting of the concrete structures.

The most important process that may affect the concrete structure during the construction phase is crack formation due to shrinkage of the cement paste during the hydration process.

Shrinkage and formation of cracks

During the first hours/days after casting of the concrete structure the temperature is increased due to the heat formed by the hydration process and consequently the concrete structure expands somewhat. After some time, the concrete cools and as a consequence also contracts. If the concrete structure is free to move, the contraction does not cause any damages. However, if one or several of the surfaces are fixed, high tensile stresses are developed in the young concrete and as a consequence cracks which penetrate the concrete may form. This process is commonly experienced when the concrete is casted on a hardened concrete slab or against rock.

Besides the penetrating cracks also surface cracks may form due to temperature variations. The surface cracks usually occur at an early stage e.g. when the form work is dismantled. The temperature differences in a concrete structure is much larger in a thick structure (over ca 500 mm) and due to this, surface cracks are more often observed in thick structures than in thinner ones. Penetrating cracks on the other hand can occur in both thick and thin structures (Emborg and Bernander 1997).

In young concrete, crack formation can also occur due to early drying of the concrete. The drying results in a plastic shrinkage that is much larger than the shrinkage caused by drying at a later stage. The shrinkage results in surface cracks that can be observed within a couple of days after the concrete has been casted. In some cases plastic shrinkage can also cause penetrating cracks (Ljungkrantz et al. 1997, pp 250–254).

Finally, autogenous shrinkage can cause the formation of cracks. However, this process is usually small and occurs only if no extra water is added to the hardened concrete during curing (sealed curing) (Taylor 1997). This shrinkage is only a problem with extremely low water/cement-ratios (Neville 2000).

7.2.3 Processes that may affect the engineered barrier system during the operational phase

The operational phase comprises the period during which waste is disposed of in the repository. During this phase, several processes can cause alterations of the properties of the concrete barriers. These processes are mainly caused by interactions between the concrete, the reinforcement bars in the concrete structure and the groundwater but also the CO_2 in the atmosphere which may cause carbonation of the concrete surface. The floor of the concrete structure is also affected by mechanical loads from the waste containers. Finally, the walls of the concrete structure have to withstand the loads caused by the wet grout during grouting around the waste containers.

In the following sections processes which are of importance mainly during the operational phase are discussed. Processes which might occur during this phase but which are more important during the post-closure phase are treated in Section 7.2.5.

Mechanical forces on the base slab caused by the stacking of containers

According to the description of the Concrete repository concept (Section 7.1) the concrete structure will be cast directly on the bedrock. With this method, the entire structure will take the loads from the waste containers and distribute the forces down to rock, preventing the concrete structure from cracking.

Mechanical forces on the barrier walls from grouting of containers

During grouting, the concrete walls will be affected by a hydrostatic pressure from the grout. The magnitude of this load will depend on the height of casting, the viscosity of the grout and its density. The largest stresses will appear at the lower parts of the walls, close to the base slab.

Drying of the concrete

It is well known that concrete contracts upon drying and that the level of contraction is dependent on the level of humidity in the concrete. For that reason inhomogeneous drying of a concrete structure, i.e. when the humidity in the material differs between different parts of the construction, will cause uneven contraction of the material and as a consequence cracks may be formed in the structure. The number and width of the cracks are dependent on the magnitude of the moisture gradient which is mainly determined by the thickness of the structure and the ambient humidity.

It should be mentioned that cement, when re-wetted, the can expand and some cracks may close again. In some cases when un-reacted cement is present, continued hydration of the unreacted cement minerals may cause the cracks to seal.

Temperature variations

Cracks can also form as a result of temperature variations in the concrete structure. When heated the concrete expands and if a temperature gradient is developed over the concrete structure, cracks may form. However, in an underground facility temperature variations can be expected to be very small due to a stable temperature over the year and lack of heat generating waste. For that reason this process is judged to be of minor importance for the long-term safety of the repository.

Carbonation

Carbonation involves the reaction between the CO_2 in the air, moisture and the portlandite ($Ca(OH)_2$) causing the formation of calcium carbonate ($CaCO_3$) and a subsequent reduction of the pH in the concrete. The process may cause a densification of the concrete which could be beneficial in that it could reduce the flow of water through the structure. However, carbonation of the portlandite can initiate corrosion of the reinforcement bars due to that the passive layer on the surface of the reinforcement bars is destroyed when the pH in the concrete is reduced.

The rate of carbonation depends on four primary factors (Fagerlund 1992):

1. *Amount of material that can carbonate*. With a higher amount of material that can be carbonated the rate of the movement of the carbonation front is reduced.
2. *Amount of carbon dioxide in the atmosphere*. The carbonation rate increases with increasing levels of CO_2 in the surrounding atmosphere or CO_3^{2-} in the groundwater.
3. *Density of the concrete*. The gas diffusion rate is slower for a high density concrete than for a more porous one and hence the rate of carbonation is slower for a more dense concrete.
4. *Relative humidity in the concrete*. For the carbon dioxide to react there has to be a supply of moisture and the optimal humidity for carbonation is between 50 and 60% relative humidity. Carbonation is very slow for very dry or very wet concrete.

The carbonation process is usually seen as a carbonated front with an ingression rate that is often described with Equation 7-1:

$$x = k \cdot \sqrt{t} \qquad 7\text{-}1$$

where x is the depth of carbonation, k is a constant that depends on the four parameters presented above, and t is the time.

However, differences can appear due to inhomogeneities in the concrete matrix such as cracks and aggregates. Despite this, corrosion of the reinforcement usually does not appear before the carbonation front has reached the steel even if a crack would reach a rebar. This is due to a combination of that the corrosion products formed will seal the crack again and that the zone around the reinforcement bar is re-alkalised by the non-carbonated cement paste (Fagerlund 1992).

Chloride ingress

Chloride is present in the groundwater and diffuses readily into concrete where it can cause mineral alterations or initiate corrosion of the reinforcement bars or other metallic components present in the concrete.

The diffusion rate of the chloride ions in the concrete is dependent on several factors such as:

- Ion concentration of the saline water.
- The ability of the concrete to bind ions.
- The moisture condition.

In general, the most demanding conditions for a concrete construction are experienced in the so-called splash zone, i.e. in the zone where the concrete experiences a sequence of wetting and drying. For an underground repository this would correspond to a process where chloride containing groundwater drips onto the concrete structures where it evaporates leading to a gradual increase in the chloride concentration in the concrete. Under these conditions the chloride concentration in the concrete may become much higher than the concentration in the groundwater. Through diffusion, the chloride concentration will also increase deeper inside the concrete structure causing an increased risk for chloride induced corrosion of the reinforcement bars.

Finally, salt ingression in concrete may also cause so-called salt spalling which occurs when salt that has accumulated in the concrete structure crystallises as the concrete dries. The crystallization of the salt can result in high stresses and subsequent formation of cracks in the concrete.

Alkali aggregate reactions

The ballast mainly consists of aggregates, gravel and stone. Some types of aggregates are reactive in contact with alkali e.g. opal, flint, rhyolite or other types of amorphous silica based minerals. When in contact with a high alkali material such as cement, a reaction occurs at the aggregate surface and a gel is produced. This gel may expand if wetted and if the gel is viscous the reaction product can be pressed out through existing cracks. However, in some cases the expanding gel may crack the concrete. Reactive ballast is not common in Sweden but some reactive minerals can be found mainly in parts of the Scandic Mountains and in the province of Scania (Fagerlund 1992).

Metal corrosion

Concrete is a hard but brittle material with a high compressive strength but a low tensile strength. To increase their tensile strength of concrete structures, reinforcement bars (mainly made of steel) are embedded in concrete structures.

Owing to the high alkalinity in the concrete, steel is passivated and the corrosion rate of steel reinforcement bars is low. However, the passivation layer of the reinforcement bars can be destroyed by different processes leading to an increased corrosion rate. Examples of such processes are carbonation or chloride ingression. The time it takes for these processes to initiate corrosion depends on the:

- Ion concentration of the saline water.
- The ingression rate.
- The concretes ability to bind ions.
- The threshold for initiation.
- The concrete covers thickness.
- The moisture condition.

When the threshold has been reached, it is mainly the level of humidity and temperature that determines the corrosion rate.

During the operational period of the repository, corrosion involves the reaction between the iron in the reinforcement bars and ambient oxygen according to Equation 7-2.

$$4Fe(s) + 3O_2 + H_2O \rightarrow Fe_2O_3\,(s) + 2FeO(OH)(s) \qquad 7\text{-}2$$

For the corrosion to be significant the relative humidity in the concrete has to be relatively high and the highest corrosion rate appears when the relative humidity is 90–95% (Fagerlund 1992). If the relative humidity increases and the concrete is saturated, the corrosion rate will be reduced due to a limited access to oxygen. When humidity levels decrease and the concrete dries, the corrosion rate will be reduced but corrosion can proceed even at fairly low humidity levels, especially if the concrete contains slag, silica fume or fly ash.

The corrosion products can either be transported away by diffusion in the pore water or form a layer of solid products on the steel bars. The former may cause the formation of channels in the concrete structure whereas the latter may cause the build-up of a pressure inside the concrete structure and eventually the concrete will crack (Betongföreningen 2007). These cracks are normally found in the surface layer of the concrete due to the corrosion of the outermost layer of reinforcement bars.

7.2.4 Processes that may affect the engineered barrier system during the backfilling and sealing phase

During the short backfilling and sealing phase the most important degradation mechanism is caused by external or internal mechanical forces acting on the walls, lid and bottom slab of the repository. These forces are mainly caused by the hydrostatic pressure when the cavern is filled with groundwater, pressure from grouting around the waste containers and by the backfilling of the repository.

Forces caused by the grouting of the waste containers

When the space between the waste containers and between the waste containers and the walls of the concrete structure is filled with grout pressure will be exerted on the concrete walls. The magnitude of these forces is dependent on the density and viscosity of the grout as well as of the height of the wet grout.

Forces caused by the backfilling of the repository with concrete

When the repository is backfilled with concrete, external forces will act upon the concrete structure. Any damage to the concrete barrier at this stage will be complicated to restore. However, due to that it is expected that the concrete structure will be filled with waste and grout at the time of backfilling it can be assumed that the forces exerted upon the concrete structure will not have any significant impact of the mechanical integrity of the concrete structure.

7.2.5 Processes that may affect the engineered barrier system during the post-closure phase

During the post-closure period of the repository many different chemical and mechanical processes may alter the chemical and mechanical properties of the engineered barrier system in the repository. In this section, processes that are expected to be of importance during the post-closure phase are discussed.

Mechanical forces caused by the groundwater pressure

After that the cavern has been backfilled with concrete the groundwater will, with time, fill the voids. When the cavern is filled with water and equilibrium has been reached the water pressure will correspond to a water pillar of about 500 metres, corresponding to about 5 MPa. However, as long as the waste has been grouted it is not expected that the forces exerted upon the concrete structure by the groundwater will have any significant negative impact on the mechanical integrity of the concrete structure.

Mechanical forces caused by rock movements

Rock movements can be either in the form of large deformations in the rock or spalling. As the repository will be backfilled with concrete the process of concern is large deformations in the rock mass. This is due to that the entire concrete structure is cast directly against the rock wall and that any deformation in the rock will be transferred directly to the concrete structure. Spalling, on the other hand, are considered very unlikely to cause damage to the engineered barrier system.

Mechanical forces on the barrier walls from grouting of containers

Mechanical forces on the barrier walls from grouting of containers are not a problem during the post-closure period because the grout has hardened.

Mechanical forces from processes inside the concrete structure

Several different processes that can occur inside the concrete structure can result in internal pressure being exerted on the concrete walls in the repository. These processes can be either macroscopic and affect the entire structure or be acting on a microscopic scale, i.e. affecting only a very small part of the concrete structure. An example of the former is a high internal gas pressure from the anaerobic corrosion of metals, whereas local formation of swelling minerals, or spalling caused by the corrosion of reinforcement bars are examples of the latter.

Leaching of concrete

Leaching, i.e. the chemical dissolution of crystalline phases and amorphous minerals in the cement paste by the groundwater and the subsequent diffusion of the dissolved chemical species out of the concrete structure, is a slow but inevitable process in an underground repository. The leaching may result in an increased porosity of the concrete and can cause a reduction of concrete strength.

Besides the alteration of the mineralogical composition of the cement paste, this process also leads to a gradual decrease of the pH in the cement pore water, see e.g. Höglund (2001) and Cronstrand (2007).

Typically three phases in the leaching process can be identified:

- Dissolution and transport of the alkali hydroxides and a reduction of pH from about 13.5 to 12.5.
- Dissolution and transport of the portlandite. As long as portlandite is present, the pH will be buffered at about 12.5.
- Incongruent and finally congruent dissolution of the CSH-phases, i.e. the main strength bearing component in hydrated cement, and a gradual decrease of pH from 12.5 to about 10.

Besides the influence of site-specific properties such as groundwater composition the leaching rate of the concrete depends on factors such as the density and porosity of the concrete as well as the frequency and width of cracks in the material.

Leaching will after very long times lead to that the concrete structure loses its strength since the strength bearing components are dissolved, but also to the dissolution of the passive layer on the surface of the reinforcement bars when the pH drops causing the corrosion rate to increase.

Chloride ingress

Chloride ingress is described in Section 7.2.3.

Sulphate reactions

Sulphate reactions involve the formation of expansive minerals such as Ettringite or Thaumasite through a reaction between sulphate present in the groundwater and the aluminates in the cement paste. The process may cause the formation of cracks in the concrete.

In Sweden, the natural sulphate concentration in the groundwaters is low and often below the concentration which is required for sulphate attack to occur, about 200 mg/litre (Fagerlund 1992). However, in a repository for radioactive waste, the degradation of waste components might cause the formation of higher amounts of sulphate.

Reactions with other types of salts

Besides sulphate, carbonate and chloride also other types of salts such as those containing e.g. ammonium or magnesium may cause degradation of the concrete. Reactions involving these types of salts are rare but they may cause the dissolution of the calcium hydroxides and surface damages as well as the formation of swelling minerals and crack formation (Fagerlund 1992).

Alkali aggregate reactions

Alkali aggregate reactions are described in Section 7.2.3.

Metal corrosion

During the post-closure phase, the metals present in the form of waste, waste containers and/or reinforcement bars in the concrete structures will corrode. During the post-closure period the dominating corrosion process is anaerobic corrosion, Equation 7-3.

$$3\,Fe(s) + 4\,H_2O \rightarrow Fe_3O_4(s) + 4\,H_2(g) \qquad 7\text{-}3$$

In this process the corrosion of 1 µm over an area of 1 m^2 results in the formation of about 4.5 litres of $H_2(g)$. The consequences of the formation of gas are further described in the subsequent section *Gas formation*.

Initially, under anoxic, alkaline conditions the corrosion rate is low due to that the metal is passivated by the high pH in the concrete. However, during the long periods of time carbonation, chloride ingress or leaching may cause the destruction of the passive layer on the metallic components and the corrosion rate will increase.

The corrosion can either lead to the formation of cavities if the corrosion products are transported away or to cracking of the concrete structure if solid corrosion products are formed on the surface of the steel components.

Degradation of organic material

Degradation of organic materials may lead to the formation of gases such as CH_4 and CO_2 or to that chemical species which are aggressive towards the components of the engineered barrier system are formed. Depending on the type of organic material, different species may be formed. However, the amount of organic material in the future SFL is estimated to be rather low and this process will thus be of a minor importance for the long-term performance of the repository. This statement is also based on that it is currently not foreseen that organic additives e.g. superplasticizers will be used in concrete or grout. If this is reconsidered during design, degradation of organic material can be a more significant issue.

Gas formation

Gas can be formed either as a consequence of anaerobic metal corrosion or by the microbial degradation of organic materials. The formation of large amounts of gas in the repository may lead to the build-up of high pressure and a subsequent formation of cracks in the concrete structure. The gas generation may also push out a certain volume of potentially contaminated water through the concrete structure into fractures in the surrounding concrete backfill.

Freezing

Freezing may completely destroy a concrete structure if permafrost reaches repository depth and the amount of freezeable water is sufficient. However, the Concrete repository is planned to be located at a depth where it will not suffer from freezing during future glacial periods. This process is thus neglected.

7.3 Engineering principles

In Section 7.2 a number of chemical and mechanical processes that could change the chemical and mechanical properties of the concrete in the engineered barrier system were identified. The possible negative effects of many of these processes can be reduced through a correct choice of concrete composition and fabrication method for the concrete structures. In Section 7.3.1 the influence of the composition of the concrete is discussed and in Section 7.3.2 engineering methods are treated.

Of general importance in the choice of material and method for the construction of the concrete structures is to avoid the formation of cracks. In order to achieve this, efforts have to be focused on minimizing shrinkage, eliminate weak zones (i.e. cast joints, form ties and other imperfections) in the concrete during the construction of the barrier system.

7.3.1 Composition of the concrete

Concrete constitutes a mixture a several components such as cement, ballast and water but also other additives such as fly ash can be used. In this section recommendations on the choice of which types of materials that should be used and in which proportions they should be mixed are discussed.

Cement type

It is suggested that standard *Degerhamn Anläggningscement* or a similar material is used in the construction of the engineered barriers in the future SFL. This cement is a standard *Portland cement* which has a comparatively low heat generation during the hydration process and owing to its low contents of aluminates it is also resistant to sulphate attacks (Fagerlund 1992). Further, this cement type also has comparatively low contents of alkalis and it is therefore less reactive towards reactive ballast materials. However, this is not considered to be a major problem in Sweden because reactive ballast materials are quite uncommon and therefore not frequently used.

Cement content

The cement content in the concrete affects the amount of heat generated during the hydration process and thus the formation of cracks in the young concrete, Section 7.2.2.

In order to reduce heat generation and crack formation in the young concrete, the cement content should be kept as low as possible without jeopardising the properties of the concrete.

Amount of ballast and ballast composition

It is recommended that non reactive ballast is used in order to avoid alkali-ballast reactions, Section 7.2.3. It is also recommended that a large amount of ballast is used and that the fraction of large aggregates is high in order to reduce the total shrinkage of the concrete structure.

Water/cement ratio

In order to prevent or reduce the ingression of ions such as chloride, sulphate or carbonate into the concrete a dense concrete e.g. so-called *waterproof concrete* with a water/cement-ratio below about 0.55 should be used (Fagerlund 1992). Even though the properties of the concrete can be further improved if an even lower water/cement-ratio is used, a water/cement-ratio below 0.4 is not recommended due to an increased risk of autogenous shrinkage.

The use of a concrete with a low water/cement-ratio has several other advantages compared to a concrete with a higher water/cement-ratio such as increased compressive and tensile strength as well as a higher resistance to leaching.

Other additives

Different types of mineral additives, such as fly ash, slag or silica fume can be used to reduce the hydraulic conductivity and the porosity of the cement matrix. Concretes containing large quantities of slag are often considered as alkali and sulphate resistant. However, the long-term properties of concrete containing mineral additives are less well known.

7.3.2 Construction of the engineered barriers

Besides choosing the most optimal composition of the concrete, the casting process itself is also very important for the final properties of the concrete structure. In this section the most important aspects concerning the casting of concrete structures in an underground repository are discussed.

Casting of the concrete structure can be done either using traditional casting or slip form casting. Since the final design of the concrete repository has not yet been determined, it is not possible to give a final recommendation on which casting method to use. Instead brief descriptions of the two methods are presented together with some information about their respective benefits and drawbacks.

Traditional casting

Traditional casting utilises an on-site built formwork, which can be built in one stage before casting, or in several stages as the casting proceeds.

Continuous or sequential casting

If the entire formwork is built in one stage before casting, the concrete may be difficult to consolidate properly due to the presence of reinforcement bars and formwork ties. However, if the building of the formwork is divided into sections, the casting process will most likely have to be interrupted and joints have to be accepted. In order to strengthen and seal the joints, several different techniques can be used in combination with traditional reinforcement. However, because the sealant will degrade over time leakage points may be formed at the position of the joint.

Form ties and formwork struts

During casting, the formwork will experience a high hydrostatic pressure from the fresh concrete. To avoid a collapse of the formwork, form ties may be installed. A form tie often constitutes a steel rod which is installed prior to casting and which will be left in the concrete. However, due to that the form tie penetrates the concrete structure there is a risk for the formation of a zone with a higher hydraulic conductivity, once the form tie starts to corrode. For that reason, form ties should preferably be avoided.

Whether form ties are used or not, formwork struts have to be installed in order to support the formwork. The outer formwork wall may be stabilized by struts supported by the surrounding cavern walls, while for the inner formwork wall struts may be installed diagonally, supported by the base slab. This requires that the base slab have cured enough and gained sufficient strength to withstand the forces from the struts.

Casting strategy

When casting the concrete there is a risk that the concrete mass consolidates in an undesired way. This may result in the formation of cavities beneath the reinforcement bars or beneath the form ties. To prevent this, the casting heights should be regulated depending on the concrete composition and the vibration requirements.

Slip form casting

As an alternative to traditional casting, slip-form casting can be used. Here a slip-form is climbing up alongside the casting front aided by a number of hydraulic jacks. The formwork is usually 1–1.5 metre high and made out of plywood or metal sheets. Slip-form casting requires much less formwork material than traditional casting and can also be accomplished without the use of form ties. Finally, the casting is done continuously and consequently no joints are formed.

Slip-form casting requires that the curing properties of the concrete are well defined and that a continuous production and deliverance of concrete can be secured during the entire process. The climbing speed of the slip-form depends on factors such as the concrete properties, but is normally 50–300 mm per hour. Typically, each casting stage (i.e. each time the concrete is poured into the formwork) corresponds to a height of about 150–200 mm and the time between each stage is about 2 hours. Assuming that the concrete repository structure (the internal wall neglected) is about 160 metres long and about 16 metres wide with a wall thickness of 0.5 metre, the total required volume of concrete at each casting stage is estimated to roughly 36 m^3, corresponding to about five standard trucks every two hours.

Concrete reinforcement

Normally a concrete structure is reinforced by the use of steel bars which are embedded in the concrete during the casting process. However, as has been shown in Section 7.2 the reinforcement bars will corrode over time, causing either the formation of cavities or cracks in the concrete structure. In this section, different aspects related to the design of the reinforcement of the concrete structures are discussed.

Standard steel bar reinforcement

The use of standard steel bar reinforcement is a well known practise and knowledge on design and installation aspects are available. The use of steel bar reinforcement will allow for the use of traditional casting techniques due to that the joints can be reinforced and consequently crack formation in the joints will be restricted. However, due to corrosion, the steel bars will lose parts of their strength which may cause the joint to open up and the flow of water to increase.

Thickness of the layer covering the reinforcement bars

The thickness of the concrete layer that covers the outermost layer of reinforcement bars determines the period during which the steel is still in a passive state and the corrosion rate low. The main benefits with a thick covering layer is that the time before the chlorides and other aggressive chemical species reach the reinforcement bars is prolonged, but also processes which reduce the pH in the concrete surrounding the reinforcement bars, such as leaching and carbonation, are delayed.

Alternatives to steel bar reinforcement

Instead of steel bars, alternative materials can be used. Two options are available: either the concrete structure is designed without the use of reinforcement or with the use of alternative reinforcement materials such as mineral, carbon or plastic fibres. However, steel fibres can also be used.

Currently, the level of knowledge of the long-term properties of alternative reinforcement materials is not considered sufficient to propose the use of such materials in a repository for nuclear waste.

Casting a structure of the intended size and function without any reinforcement at all will require significant efforts in material and process development. Currently, development of methods for casting of similar concrete structures is ongoing as part of the extension project for SFR, where one option for the construction of the caissons in the planned 2BMA cavern is to use concrete without reinforcement.

Cooling of the concrete

As mentioned in Section 7.2.2, heat will be generated during cement hydration causing an expansion of the structure. The heat generation and subsequent cooling may cause the formation of cracks in the concrete structure. In order reduce the risk of cracking different methods can be used. In Section 7.3.1 it was suggested that the heat generation could be reduced through an optimal formulation of the concrete but also engineering methods can be used.

As long as the thickness of the concrete structure is below approximately 500 mm the surface cooling through the formwork can be sufficient to prevent an extensive temperature increase during hydration. However, cooling can be improved if a steel formwork is used but also by the use of a cooling system where cooling pipes are embedded in the concrete. However, the latter may cause the formation of conductive channels through the concrete structure unless they are properly sealed or removed once no longer in use.

Injected concrete

As an alternative to traditional concrete, injected concrete may be used. Compared to traditional concrete the injected concrete is separated into larger aggregates and the cement paste. The larger aggregates are pre-packed in the formwork and thereafter the cement paste is injected. Due to this, the bigger aggregates constitute a skeleton in the concrete that prevents shrinkage of the structure. However, due to shrinkage of the cement paste and the subsequent formation of micro cracks, the permeability of the structure would probably be higher than ordinary concrete.

Gas vents

As mentioned in Section 7.2.5 anaerobic corrosion of metals in the concrete structure will generate hydrogen gas, which has to be transported out of the repository. If this transport cannot be accomplished a high gas pressure may be formed inside the concrete structure which may force the concrete structure to crack.

If the gas formed cannot be transported through the concrete itself due to insufficient permeability, gas vents have to be installed. The detailed design of such vents is dependent on the estimated rate of gas formation and the gas permeability of the concrete, and consequently no details can be presented here. However, the vents which are planned to be used in the silo in SFR can be used as an example. Here, the silo is filled with a gas permeable grout though which the gas is transported to the top of the silo. In the lid, sand-filled holes are constructed through which the gas is released to the backfill of the rock vault, preventing any damage to the concrete silo, see Figure 10-6.

Engineered corrosion protection methods

As a mean to reduce the corrosion rate, primary during the operational phase, a cathodic protection system can be used. These systems are generally designed for each specific case and typically constitute sacrificial anodes or an active electrical system.

7.4 Grouting of the waste containers in the repository

When the waste containers have been placed in the repository, the space between the waste containers and between the waste containers and the barrier walls will be filled with a grout. This can be done when each compartment has been filled with waste or at any time prior to the backfill and closure of the repository. During this process care must be taken in order to avoid that the hydrostatic pressure from the wet grout causes the engineered barrier walls to crack or collapse. In this section issues related to the grouting process are discussed.

7.4.1 Properties of the grout

The compressive strength of the grout should be high enough to support the concrete barrier against the external forces occurring during backfill and resaturation of the repository. In addition the grout should have a high gas permeability to provide for transport and release of the gases formed in the repository.

7.4.2 Grouting of the waste

During grouting the walls are affected by the hydrostatic pressure of the wet grout. For that reason, the grouting should be done in sequences in order to reduce the forces on the barrier walls. However, care must also be taken to avoid the formation of imperfections or cavities that may reduce the mechanical strength of the grout.

7.5 Protection of the engineered barriers during the operational phase of the repository

As shown in Section 7.2 several processes may influence the properties of the concrete barriers in the repository. Many of these processes such as shrinkage, carbonation, alkali aggregate reactions, leaching and corrosion of reinforcement bars are dependent on the presence or absence of water. Water or moisture can come in contact with the concrete structure during operation from the cavern walls, the rock bed and from the vented air. In this section methods which can be used during the operational period of the repository to prevent, limit or delay these processes are discussed in order to provide the basis for the future design of the concrete repository.

7.5.1 Control of the relative humidity and temperature in the repository

To reduce the risk of cracking during the operational phase of the repository, the structure should be protected from extensive drying and large temperature gradients. The optimal condition would be a high relative humidity and a stable temperature during all seasons in order to prevent the formation of cracks due to drying or large temperature variations.

It is therefore recommended that the ventilation system is equipped with humidity and temperature control to ensure a stable climate in the repository during all seasons.

However, in the efforts of preventing shrinkage and crack formation it must be remembered that the corrosion rate is the highest when the relative humidity is between 90–95% (Fagerlund 1992).

7.5.2 Prevention of groundwater intrusion

In order to prevent the intrusion of groundwater different methods may be used. In a repository, the groundwater may either enter the repository through the ceiling and drip down on the barrier structures or accumulate beneath the concrete structure. The sequence of dripping and drying may lead to high concentrations of chloride at the concrete surface and eventually, through diffusion, also deeper inside the concrete.

In SFR a tunnel cloth has been installed in 1BMA and in the silo to prevent the groundwater from dripping down on the barrier constructions during the operational phase. A similar solution can be used also in the future SFL.

In order to prevent the water from being sucked into the bottom slab of the concrete structure, a well functioning drainage layer needs to be installed beneath the concrete structure. This drainage layer has to be controlled on regular intervals in order to ensure its function over the entire operational phase prior to backfill, closure and sealing of the repository.

Figure 7-2. *The tunnel cloth installed in 1BMA used to protect the concrete structure from groundwater dripping from the ceiling of the rock vault.*

Figure 7-3. The drainage layer between the concrete structure in 1BMA and the rock wall. This drainage layer also continues underneath the concrete structure.

7.6 Backfilling of the repository

Backfilling of the repository with concrete serves the purposes of protecting the engineered barriers from rock spalling and increasing the overall retention capacity of the repository. The backfill serves together with the concrete structures as the engineered barrier in this concept. In this section the choice of backfill material and method for backfilling of the repository is discussed.

7.6.1 Properties of the backfill material

The concrete used as backfill material need to support the safety functions as outlined in Section 7.1. The backfill material should preferably also be gas permeable to facilitate transport and release of the gases formed within the repository. The mechanical properties of the backfill are expected to be of less importance.

7.6.2 Design and method

As mentioned in Section 7.2.5, rock movements occurring in the vicinity of the concrete repository may be transferred to the concrete structure since the backfill material is cast in direct contact with the rock wall. This could lead to the formation of ruptures in the concrete volume.

In order to prevent this, deformation zones between the backfill and the rock can be installed. As an alternative, the concrete structure and backfill could be divided into separate compartments separated by buffer zones, where weak points in the bedrock are identified.

The process of backfilling the entire rock vault with concrete will be a challenging task and two alternative technical solutions have been identified. The first involves filling the entire rock vault with wet concrete, whereas the second involves filling the rock vault with pre-cast solid concrete blocks between which wet concrete is injected to form a solid monolith.

Which of these methods that is the most suitable cannot be determined at this stage, mainly because no requirements have yet been formulated for the backfill material. However, filling the entire repository with pre-cast solid concrete cubes will definitively have a big advantage from a logistic point of view. Another advantage is that the amount of heat that will be generated in the repository during backfill will be dramatically reduced if pre-cast cubes are used compared to if the entire repository is backfilled with wet concrete.

7.7 Summary and conclusions

In this chapter a number of aspects concerning the concrete repository have been discussed. From the identification of the processes of relevance, technical aspects which could be used to control or mitigate these processes have been discussed.

To summarise, it has been found that the following main aspects should be considered in the design and construction of the Concrete repository:

- Degerhamn anläggningscement, or a similar material, exhibits promising properties both in terms of construction and in the long-term, and can be used as a starting point in the development work henceforward.
- A low cement content in the concrete is beneficial in order to avoid heat generation and shrinkage during the hydration of the concrete.
- A low water/cement-ratio is beneficial in order to reduce the porosity of the concrete.
- The use of pre-cast concrete blocks in combination with grout represents a plausible method to backfill of the repository, and needs to be further explored.
- The gas permeability of the grout used to fill the space between the containers inside the concrete structure is an important factor to consider when developing the grout recipe.

8 The Clay repository

In this chapter the conceptual design of the Clay repository and the intended function of the barriers are first described. This is followed by identification of the processes which may affect the barrier properties during the construction, operation, backfilling and sealing and the post-closure phases. With these processes forming a background, the choice of bentonite type and its quality as well as alternatives for design and construction methods of the repository are discussed.

8.1 General description of the Clay repository

The Clay repository is a geological disposal concept which is based on the use of large amounts of bentonite clay as a low permeability medium enclosing the LL-LILW. The primary safety function of this concept is retardation. The purpose of the barriers is to limit the flow of groundwater through the waste thus making diffusion the predominant transport process for radionuclides.

8.1.1 Main components of the engineered barrier system

A reinforced concrete base slab is placed on granite pillars, which are raised on the bottom of the vault. A concrete wall structure, similar to the one used in the Concrete repository, Chapter 7, is erected on the base slab. The waste is placed inside the structure.

No bentonite is placed in the repository until the time of closure. At closure, empty voids between waste packages are grouted and a concrete lid is placed on the structure. Bentonite blocks are placed beneath the base slab as well as on the sides and on top of the disposal structure. The top part of the vault is filled with bentonite pellets. The bentonite specifications are discussed in Section 8.3.

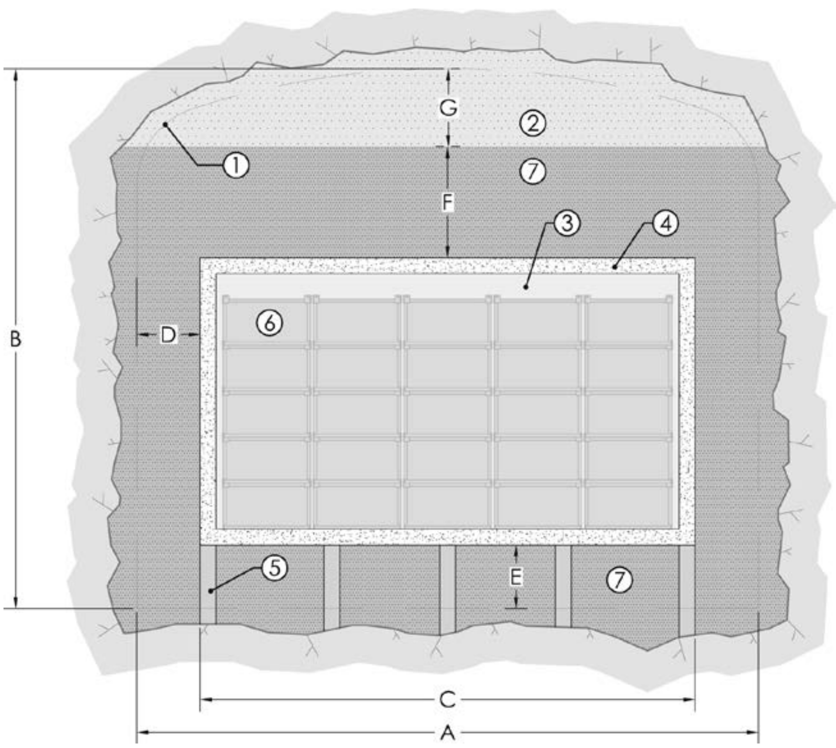


Figure 8-1. *Cross-sectional view of the Clay repository. Legend: 1) Theoretical tunnel contour. 2) Bentonite pellets. 3) Grout. 4) Concrete structure for the operating period (0.5 metre). 5) Granite pillars. 6) Waste containers. 7) Bentonite blocks. Approximate dimensions: A = 20 m, B = 17 m, C = 16 m, D = 2 m, E = 2 m, F = 3–4 m, G = 2–3 m.*

The purpose of the concrete structure is to provide radiation protection during the operational phase and it is not credited any long-term safety function. The thickness of the clay barrier is a minimum of two metres. Therefore, it is assumed that the interaction between concrete and bentonite will have a negligible effect on the long-term performance of the clay barrier.

8.1.2 Safety functions of the engineered barriers

The safety functions of the concept are:

- Low hydraulic conductivity in the bentonite.
- Low diffusivity in the bentonite.
- Strong sorption of radionuclides in the bentonite.
- Filtering of colloids in the bentonite.

In addition to this, the natural barrier – the bedrock – will contribute to the primary safety function retardation. No safety function is assigned to the waste or the containers.

The concrete structure is important during the operational and backfilling phases but is not credited with a long-term safety function.

8.2 Design considerations

8.2.1 Processes that may affect the engineered barrier system, overview

In order to ensure the long-term function of the engineered barrier system, both materials and methods for construction have to be chosen with great care.

As mentioned in the preceding section, the main safety functions of the Clay repository are low hydraulic conductivity and strong sorption of radionuclides in the bentonite, and slow diffusion through the bentonite. In order to achieve this, great care has to be taken on the choice of type and quality of bentonite and on the design and location of the repository to secure the function of the engineered barriers over the entire operational lifetime of the repository.

During operation, backfill and sealing as well as during the post-closure period, different processes may influence the properties of the materials in the engineered barrier system. The most important processes are discussed in Sections 8.2.2–8.2.5.

8.2.2 Considerations for the construction phase

The most important prerequisite for the Clay repository is that the chosen rock volume is suitable for the construction of one sufficiently large rock vault or a number of smaller rock vaults. The use of a number of smaller rock vaults could make both the utilisation of the available rock volume and the strategy for deposition of the waste more flexible compared to the use of a single large rock vault. However, the use of one large cavern will probably require the excavation of a lesser amount of rock and a lower total consumption of bentonite. Finally, hydrological properties of the bedrock are important for the installation of bentonite as well as for the long-term safety of the repository.

8.2.3 Processes that may affect the engineered barrier system during the operational phase

No processes that influence the long-term properties of the engineered barrier system of the Clay repository during the operational phase have been identified. No bentonite will be installed prior to backfill and closure.

However, if an alternative solution is chosen, where bentonite is installed already during the construction or operational phases, the situation will be slightly different. The most critical issue will then be the risk of early swelling of the bentonite due to groundwater intrusion during the operational phase. This may lead to unwanted effects on the concrete structure and the stack of waste containers. In the case that bentonite is installed beneath the concrete structure during the construction of the repository particular care has to be taken in the design of the concrete structure and the drainage of the repository.

8.2.4 Processes that may affect the engineered barrier system during the backfilling and sealing phase

Processes that need to be considered during the backfilling and sealing phase are to a large extent connected to groundwater inflow. Large water inflow can lead to early swelling of the bentonite blocks and possibly to a collapse of the bentonite block stack. However, the bentonite pellets which are installed between the bentonite blocks and the rock wall can act as a buffer for intruding water and thus mitigate these problems. Finally, the cavities and channels formed through piping and erosion during the early saturation phase will disappear as the bentonite swells and homogenises. The backfilling rate needs to be high enough to avoid the problems described above. How high rate that is necessary will, in addition to the water inflow and its distribution, depend on the detailed design, i.e. pellet filled volume and water storage properties.

8.2.5 Processes that may affect the engineered barrier system during the post-closure phase

The long-term safety of the Clay repository relies, besides the properties of the host rock, on the properties of the bentonite in the repository. No long-term safety function is credited either to the waste, the containers or the concrete structure. However, the mechanical properties of the combined volume of waste containers and the concrete structure are still of importance. The swelling pressure from the bentonite will act on the rigid volume at the centre of the cavern. The mechanical properties of the concrete structure as well as of the waste containers need thus to be designed to withstand the swelling pressure.

Processes that may affect the properties of bentonite have been investigated in detail for the Spent Fuel Repository, see e.g. SKB (2010). The following processes have been found to be of relevance for the Clay repository during the post-closure phase:

Thermal processes:

- Freezing.

Hydraulic processes:

- Gas transport/dissolution.
- Piping/Erosion.

Mechanical processes:

- Swelling/mass redistribution.
- Liquefaction.

Chemical processes:

- Alterations of impurities.
- Aqueous speciation and reactions.
- Montmorillonite transformation.
- Iron/bentonite interaction.
- Montmorillonite colloid release.
- Microbial processes.
- Cementation.

In SKB (2010) details on these processes can be found.

Since no safety function is assigned to the concrete structure there is no requirement that the bentonite should absorb the deformations associated with an earthquake.

Processes related to bentonite/concrete interaction are not as crucial for the performance of the Spent Fuel Repository as they are expected to be for the Clay repository concept. Processes related to this interaction will need to be studied in detail for this concept.

Bentonite/concrete interaction

The interaction between bentonite (and other clays) and concrete has been studied for different repository conditions. For the Clay repository, the interaction will need to be understood in detail to give basis for the design of the bentonite barrier as well as for the concrete structures necessary for the operation of the repository.

In Gaucher and Blanc (2006), a comprehensive list of laboratory experiments identifying the reaction sequences in the evolution of both the clay minerals and accessory minerals during their alteration in an alkaline environment was established.

According to Gaucher and Blanc (2006), the concrete will begin to evolve as soon as it is saturated with pore water from the geological formation, whose initial pH is close to neutral. If commercial cement materials are used, the concrete degradation will initially generate a high-pH water (pH > 13), rich in K, Na, and Ca ions. This first period will be followed by a period in which the pH is dominated by equilibrium with portlandite, $Ca(OH)_2$, (pH = 12.4), and finally by an equilibrium with the CSH-type minerals (pH ≥ 10).

The clay barrier's geochemistry, mineralogy and texture will be modified near the concrete/clay interface because concrete degradation generates a diffusive alkaline plume. Gaucher and Blanc (2006) states the following rough calculation to initially determine the dimension of the montmorillonite/concrete interaction. If we take the following dissolution reaction for montmorillonite in an alkaline medium:

$$Na_{0.33}Mg_{0.33}Al_{1.67}Si_4O_{10}(OH_2)+4.68OH^-+2H_2O \Leftrightarrow 0.33Na^++0.33Mg^{2+}+1.67Al(OH)_4^- + 4HSiO_3^-$$

The dissolution of one mole of montmorillonite consumes 4.68 moles of OH^-, 1 m^3 of concrete (OPC + unreactive aggregate) produces 8,000 moles of OH^-, and one finds 1,500 moles of montmorillonite in 1 m^3 of barrier (Kunigel V1 70% + sand 30%; dry density 1.6 g/cm^3); taking a molar volume of 220 cm^3/mole for this montmorillonite therefore gives 4,500 mole/m^3 in a mineralogically pure barrier with no porosity. This show that approximately 1 m^3 of montmorillonite is required to buffer 1 m^3 of concrete.

According to Gaucher and Blanc (2006), the studies made on natural analogues and in underground laboratories show a fairly limited spatial extension of the alkaline disturbance that is of the order of 4 cm per 100,000 years at Maqarin, Jordan.

From the interim results of the Cyprus Natural Analogue Project (CNAP), Alexander et al. (2013) concludes that it appears likely that long-term reaction of industrial bentonites by low alkali cement leachates in a repository is unlikely to impact the favourable properties of the bentonite significantly. Alexander et al. (2013) also states that it will be possible to compare these conclusions with the results of the ongoing laboratory and URL experiments on bentonite reaction in the medium term.

Implications for design

The main safety function of the clay repository is retardation. The main purpose of the clay barrier is to make diffusion the predominant transport process of radionuclides.

The objective of the design is to ensure that the main safety function of the clay concept is ensured for the entire period considered in the long-term safety performance assessment.

High bentonite density, high montmorrilonite content and large amounts of bentonite ensures that the safety function can be upheld with sufficient margin.

The following processes affect the bentonite density and or the total amount of bentonite in the cavern:

- Piping/Erosion.
- Swelling/mass redistribution (a high degree of homogenization is favourable since it increases density of the pellet fill).
- Montmorillonite colloid release.

No positive aspects associated with low bentonite density have been identified. However, if gas release is considered to be of great importance in the long term safety assessment low density may be favourable.

Hence the conclusion is that as high installed average density, high content of montmorillonite and a large mass of bentonite should be strived for.

8.3 Engineering principles

In Section 8.2 several processes that may affect the properties of the bentonite in the Clay repository were listed and discussed. The adverse effects of some of these processes can be handled through the choice of type and quality of bentonite, or through the design or the choice of construction method. In this section, material and construction options that can be used to mitigate the effects of the processes discussed above are presented.

8.3.1 Choice of bentonite type and quality

The installed bentonite will with time equilibrate with the surrounding groundwater chemistry by ion exchange rections. Hence the long term cation population in the bentonite will be dependent on the surrounding groundwater chemistry and not by the installed bentonite type. Hence the choice between Na- and Ca-bentonite should be based upon other parameters than long term safety, such as installation and manufacturing behaviour/properties and costs (Ca-bentonite is generally cheaper).

In the inital design work a MX-80 type of bentonite may be used since it is very well characterised which simplifies the inital long term safety assessment.

In general, it is assumed that high-density bentonite provides for the long-term safety of the repository. In the refined concepts for the Clay repository, this must be combined with a study of feasible installation methods.

Dry density of the bentonite

Side fill

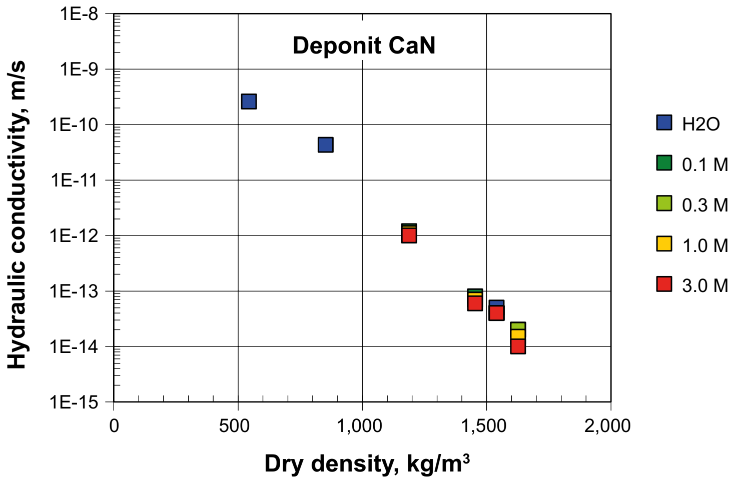
It is suggested that bentonite blocks with a dry density of 1,600–1,700 kg/m^3 is used in combination with a pellet fill between the stack of blocks and the rock wall. The manufacturing of this type of blocks with standard methods have been previously demonstrated, see for example Johannesson et al. (1995). It is estimated that the block section will be 2 m wide and that an average of 20 cm towards the rock wall is filled with pellets. With an average density of the pellet fill of 1,000 kg/m^3, the average density in the entire section will be about 1,550 kg/m^3. As shown in Figure 8-2 for a high quality Ca-bentonite, this average density corresponds to a very low hydraulic conductivity – about $5 \cdot 10^{-14}$ m/s – and a swelling pressure of more than 5 MPa.

Bottom fill

It is assumed that the volume below the concrete structure can be filled with the corresponding ratio of blocks and pellets as on the sides, resulting in the same low hydraulic conductivity and pronounced swelling pressure.

Top fill

According to the basic concept, the volume atop the concrete structure will be filled with bentonite blocks to a height of 3–4 metres, with bentonite pellets filling for the remaining dome-shaped part of the rock vault.



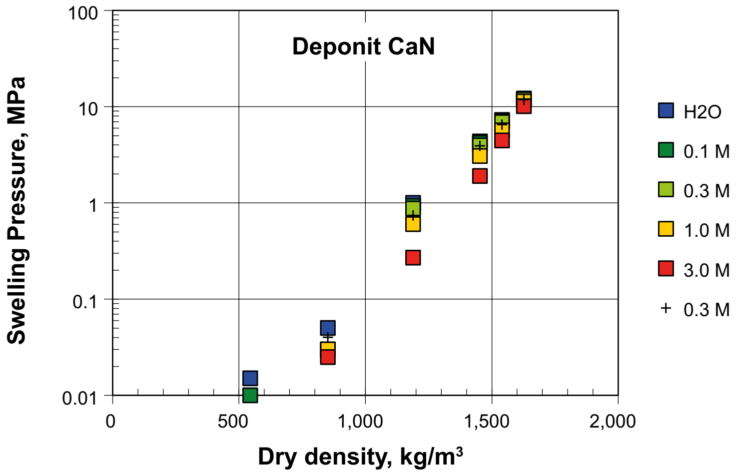


Figure 8-2. *Measured relation between hydraulic conductivity and density (upper) and swelling pressure and density (lower) at water saturation for a high quality Ca-bentonite (Deponit CaN, also denoted IBECO RWC). The legend states the concentration of $CaCl_2$ in balance with respective sample (Karnland et al. 2006).*

It is estimated that the average density for this part of the bentonite fill will be about 1,300 kg/m^3, which corresponds to a swelling pressure of just below 1 MPa. However, due to the large volumes, it is expected that a density gradient will remain in the bentonite after swelling and homogenisation. The effects of this rather large difference in swelling pressure of the top backfill section will need to be investigated.

8.3.2 Construction of the engineered barriers

In this section the most important aspects concerning the construction of a Clay repository are discussed.

Concrete structure and pillars

In the suggested design of the Clay repository, a concrete structure will be erected on pillars of granite, Figure 8-1. In Section 7.3 materials and methods for the construction of a concrete structure in the Concrete repository are discussed and much of that is also valid for the concrete structure in the Clay repository, despite the fact that this concrete structure is for operational purposes only.

However, an additional feature for the Clay repository is that the entire concrete structure will be erected on pillars. This feature certainly adds a demanding challenge to the design, which has to be dealt with in the process of designing and planning of the repository. However, constructions on pillars are common for e.g. bridges and it is therefore judged to be feasible and will not to affect the conceptual design of the Clay repository.

The reason for using granite pillars instead of a concrete foundation is that granite is undoubtedly long-term stable. Possible degradation of any concrete pillar can cause pathways for nuclide migration to the surrounding rock. The dimensions and spacing of pillars will have to be evaluated in the detailed design. How to ensure sufficient stability to stop the concrete structure from moving sideways or cracking in case of accidents will have to be handled. During operations, concrete supports anchored to the rock walls can be used for ensuring stability. Different types of temporary supports can be used during backfilling. Changing the pillar material to concrete would simplify the construction of the repository but the influence on long-term safety would need to be evaluated.

Installation of bentonite blocks and pellets

The backfilling method and time estimation presented in this section is an overview based on certain simplifications and assumptions. Further development of method and equipment for the installation of bentonite blocks and pellets will be needed. Since installation is planned to be carried out far ahead in the future, it is considered reasonable to expect that installation technology will develop until the time of installation. The installation described here aims to illustrate that the installation is possible and can be carried out within a reasonable timespan.

The bentonite blocks are transported and placed by the aid of remote controlled or autonomous vihecles. The installation of blocks around the pillars is considered to be the limiting factor, when assessing the feasibility of the installation method. Preferably, the floor of the cavern can be excavated for a smooth surface to increase fasibility for the installation.

An overarching study to estimate the time needed for installation of bentonite blocks under the concrete structure in a possible repository for intermediate short-lived radioactive waste was reported by Kjellin and von der Lancken (SKBdoc 1348196). The study is based on the following assumptions:

- Two shifts per 24 hours.
- Two forklifts work in parallel.
- Ca 17,000 blocks to be installed.
- The supply of blocks to the forklifts is not a limiting factor.
- The length of the concrete structure is 160 m.

Assuming an installation rate of 4–7 minutes per block, the installation of bentonite under the concrete structure will take 36–63 days.

When the blocks under the concrete structure are in place, the installation of bentonite in the 2 m wide space between the rock wall and the concrete structure can begin. When the volume between the rock wall and the concrete structure has been filled, the volume up to about three metres above the concrete structure is filled with bentonite blocks. The remaining spaces at the roof and between rock wall and bentonite blocks are filled with bentonite pellets.

Handling of water

In order to avoid early swelling of the bentonite during installation, a drainage system at the rock walls may be required. However, if the drainage system is shown to have significant negative impact on the long-term function of the repository, and if it cannot be removed at closure, other alternatives must be sought for.

Methods for handling water inflow to deposition tunnels are developed by SKB for the Spent Fuel Repository. The know-how developed will be utilized when doing the detailed design of the Clay repository.

Handling of gas

No special features for handling of gas are included in the conceptual design of the Clay repository.

Prior to saturation, gas can be transported through the bentonite. Gas transport for the saturated bentonite (long time after closure) is discussed in the following.

Gas which is trapped in or by the bentonite can escape by two principal mechanisms:

- If the gas production rate is low or the gas quantity small, the gas can be dissolved in the pore water and be removed by diffusion.
- If the production rate is higher or the gas quantity is larger than can be removed via dissolution and diffusive processes, a gas phase will form, the pressure will rise, and a flow path is expected to be formed through the bentonite barrier at a critical pressure.

An uncertainty in the understanding of gas transport in the bentonite concerns the number, size and spatial arrangement of the gas-bearing features and the volume (stress-strain) behaviour of the clay during gas injection. In SKB (2010) results from modelling and tests are summarized and it is concluded that the gas transport observed through bentonite can be interpreted in a number of different ways. One critical uncertainty is the break-through pressure, i.e. the pressure when the buffer opens and lets the gas through. This determines the maximum pressure that can be created within the near field of the repository. Another uncertainty is the closure pressure, the pressure at which the pathways in the bentonite close. A further uncertainty relates to the volume of water displaced during gas flow. Potential de-watering of the clay may affect the performance of the bentonite barrier.

If no active design measures of letting gas pass through the bentonite is installed and gasformation becomes an issue for the long term safety performance assessment, the gas transport processes will need to be investigated in further detail for the conditions in the Clay repository. This will yield basis for the design of the bentonite barrier.

8.4 Alternative design of the Clay repository: Bentonite cradle

As an alternative to the conceptual design of the Clay repository shown in Figure 8-1, which involves emplacement of bentonite blocks beneath the concrete structure in a backfilling campaign just before closure of the repository, the bottom fill bentonite blocks can instead be placed in a confinement already during the construction of the repository. The confinement protects the bentonite blocks from moisture during the operational period of the repository, see Figure 8-3.

The confinement lid, on top of the bentonite blocks, also acts as the floor during the operational period. The stack of bentonite blocks beneath the concrete structure – the bentonite cradle – has to be stable enough to avoid settlements and the formation of fractures in the concrete structure. The detailed design of the concrete structure will be dependent on the bentonite properties.

After the operational period, the peripheral parts of the confinement lid are removed and the backfilling of the remaining part of the cavern can begin. A schematic cross-sectional view of the backfilled repository is shown in Figure 8-4.

To protect the bentonite in the cradle from absorbing water during the operational phase, groundwater from the rock should be collected with local drains. During the operational period the water is led to a drainage that pumps out all water from the cavern. Before backfilling the cavern, the drainage pipes along the walls are dismantled to the extent possible.

One critical issue for this alternative is how stable the foundation of bentonite blocks can persist during the operation period. This issue is in common with the Super silo where the requirements on the bentonite foundation will be even more intricate. This is discussed in Section 10.5.

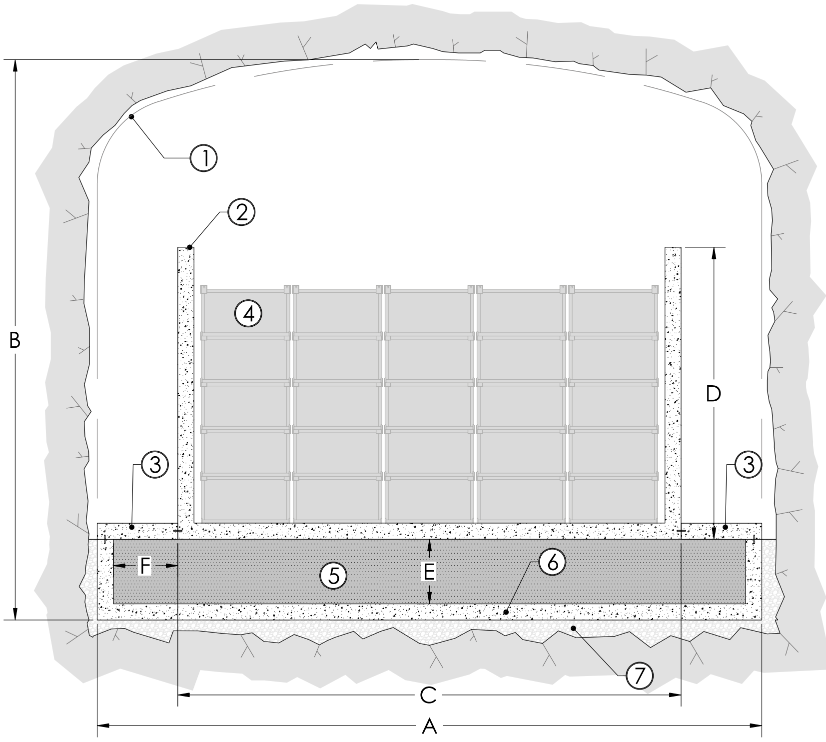


Figure 8-3. *Bentonite cradle concept during operation. Legend: 1) Theoretical tunnel contour. 2, 3 and 6) Concrete structures. 4) Waste containers. 5) Bentonite blocks. 7) Gravel. Approximate dimensions: A = 20 m, B = 17 m, C = 16 m, D = 7–8 m, E = 2 m, F = 2 m.*

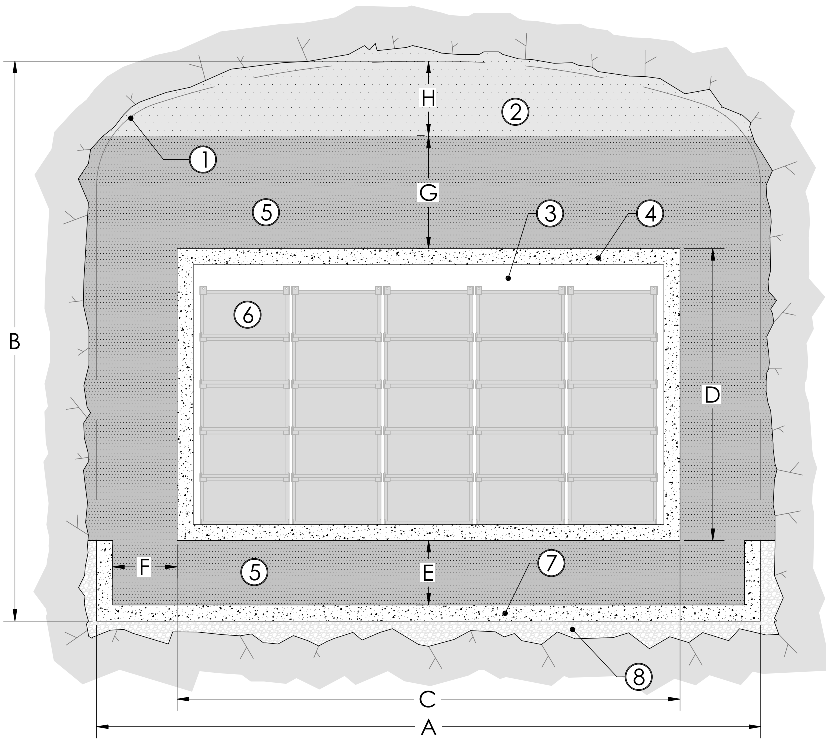


Figure 8-4. *Bentonite cradle concept after backfilling. Legend: 1) Theoretical tunnel contour. 2) Bentonite pellet fill. 3) Grout. 4) Concrete structure (0.5 m). 5) Bentonite blocks and pellet fill towards the walls. 6) Waste containers. 7) Original base slab. 8) Gravel. Approximate dimensions: A = 20 m, B = 17 m, C = 16 m, D = 7–8 m, E = 2 m, F = 2 m, G = 3–4 m, H = 2–3 m.*

8.5 Backfilling and closure of the repository

Different ways of backfilling the Clay repository with bentonite blocks and pellets have been discussed in Sections 8.3 and 8.4.

To facilitate the emplacement of bentonite backfill, a well thought out management of the inflowing groundwater is important. Since the operational drainage system has been dismantled before the backfilling campaign begins, larger water inflows from the rock walls and from the local drains from the rock may instead need to be distributed over a larger area of the rock wall using geotextiles or similar.

When the cavern has been filled with bentonite a plug that resists the bentonite swelling pressure will be constructed in the cavern opening. Since shaft, ramp and tunnel system will be backfilled short after the cavern has been backfilled and plugged no strict requirements on the plug to act as a hydraulic seal are foreseen. When the repository has been saturated by groundwater, no significant hydraulic gradients over the plug are expected.

8.6 Summary and conclusions

In this chapter the design, choices of material and installation sequences of the engineered barriers in the Clay repository have been discussed. One basic design and one alternative, the bentonite cradle have been studied.

The main advantage for the basic design compared to the alternative design is that no bentonite is installed prior to closure. The practical aspects related to the pillars, concrete structure and bentonite installation requires further investigation and development to verify the feasibility of the basic design. The basic design is at this early stage considered favourable and is recomeded as the reference design for further work.

Also the alternative design – the bentonite cradle described in Section 8.4 – is deemed potentially feasible and can be investigated further. The most important aspect of this design is the mechanical stability of the bentonite stack supporting the concrete structure.

The challenges for the bentonite backfill installation are related to achieving high enough density and high enough installation rate. The high density is needed to achieve low hydraulic conductivity and high swelling pressure, and to improve the robustness of the bentonite to the various processes in the repository. In order to further increase the density of the bentonite barrier methods of installing blocks also at the roof of the cavern should be developed. High installation rate is necessary to avoid practical problems mainly related to the effects of water inflow during installation.

Generation of gas in the LL-LILW in relation to gas transports in a saturated bentonite barrier will need further studies.

9 The Gravel repository

9.1 General description of the Gravel repository

The Gravel repository is a geological disposal concept which is based on the use of a hydraulic cage as a single engineered barrier. The hydraulic cage is constructed using a highly permeable medium (gravel). The hydraulic conductivity for the material used shall be 10^{-5} m/s or greater. The purpose of the barrier is to limit the release of radionuclides by limiting of the groundwater flow through the waste. Instead, the flow of groundwater is directed around the waste containers, i.e. in the permeable gravel. The schematic layout (cross-sectional view) of the Gravel repository is shown in Figure 9-1**.**

The purpose of the gravel is to create a hydraulic cage with a high hydraulic conductivity. This function should be upheld as long as possible or for the time span considered in the analysis of long-term safety.

The natural barrier – the bedrock – will contribute to the primary safety function retardation. However, siting of a Gravel repository can be intricate, since a homogenous rock mass without faults and a minimum of water bearing fractures will be of importance for the function of the hydraulic cage. This can have impact on the siting of the repository, since the repository is preferably located where no intersecting faults are likely to be found.

9.1.1 Main components of the engineered barrier system

The base slab is designed to take the load from the waste containers as well as from transport vehicles. During operation, the waste containers are deposited directly on the base slab. The foundation for the base slab is a shot rock/gravel bed, which will be a part of the hydraulic cage. Expansion joints are constructed in the base slab to permit movements.

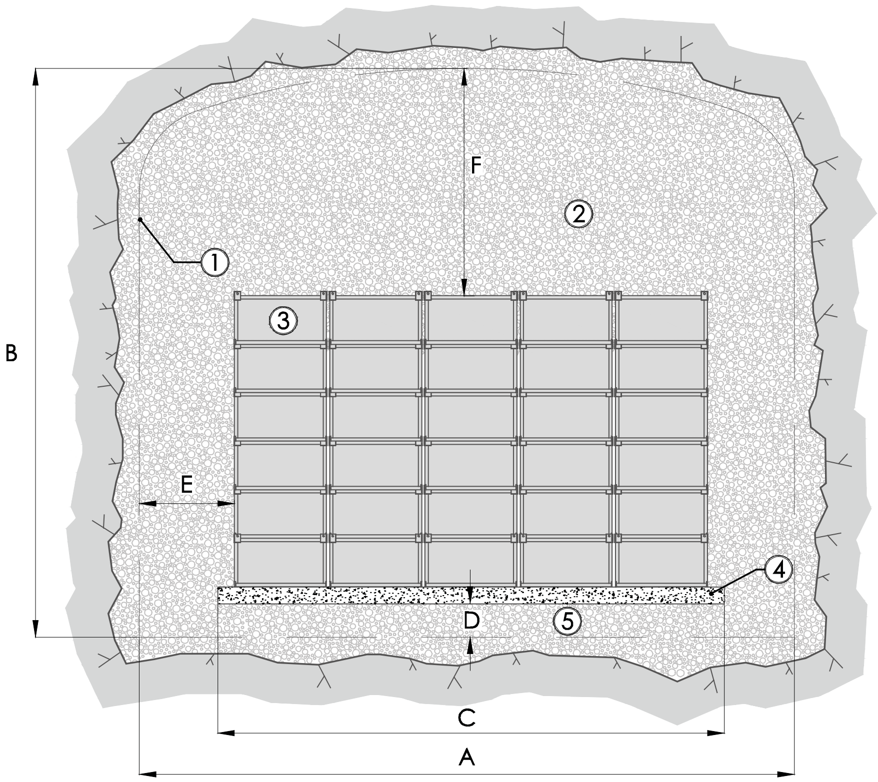


Figure 9-1. *Cross-sectional view of the Gravel repository. Legend: 1) Theoretical tunnel contour. 2) Gravel. 3) Waste containers. 4) Concrete base slab. 5) Gravel or crushed rock. Approximate dimensions: A = 20 m, B = 17 m, C = 15 m, D = 1 m, E = 2.5 m, F = 5–10 m.*

At closure the free space between the waste containers and the rock is backfilled with a gravel material with high hydraulic conductivity to create a hydraulic cage around the waste. The basic design entails the use of quarried material (crushed rock) with grain size spanning from 16 to 32 mm, which is a standard product in the construction industry. This material has a low amount of fine sized material, which provides for a relatively high hydraulic conductivity. Fines can also be further reduced by washing of the quarried material. The largest grains are still small enough not to create problems with inhomogeneity or causing damage to the waste containers. The material in the individual grains is stable and will be a stable base for the structure.

The final repository can either consist of one or several caverns depending on site conditions and properties of the waste and the containers.

9.1.2 Safety functions of the engineered barriers

The primary safety function of the Gravel repository is retardation. This is achieved by the hydraulic cage, which provides high hydraulic conductivity and therefore directs the water around the deposited waste.

The hydraulic cage is designed to limit the groundwater flow through the waste and thus limit the transport of radionuclides. However, this requires that the hydraulic conductivity of the waste containers is much lower than the hydraulic conductivity of the cage. The integrity of the waste containers needs to be maintained for a sufficient period of time. The conditioning of the waste is therefore crucial in maintaining the safety function of the concept.

No safety function is assigned to the concrete structures in the cavern, such as the base slab.

9.2 Design considerations

9.2.1 Processes that may affect the engineered barrier system, overview

In order to ensure the long-term function of the engineered barrier system the materials used and methods for construction have to be chosen with great care.

As mentioned in the preceding section, the main safety function of the gravel repository is to decrease the flow of water through the waste and instead direct it to the gravel-filled volume that surrounds the waste containers.

During operation, backfill and sealing as well as during the post-closure period, different processes may affect the properties of the material in the engineered barrier system. The most important processes are discussed in Sections 9.2.2–9.2.5.

9.2.2 Processes that may affect the engineered barrier system during the construction phase

The only degradation process that has been identified during the construction of the Gravel repository is clogging of the gravel beneath the concrete structure, due to careless handling of materials that can cause clogging, such as grout and concrete.

9.2.3 Processes that may affect the engineered barrier system during the operational phase

As the gravel will be partly exposed during the operational phase, there is a risk for clogging of the gravel bed beneath the concrete structure which may influence the conductivity already during this phase. Clogging can be caused by any of the following processes:

- Clogging of cage medium by dirt from operations e.g. dust, debris etc.
- Clogging of cage medium by bacteria and algae (rock mud).
- Mechanical wear of the cage medium grains makes the grains release small fragments of material, which cause clogging.

However, since the bulk of the gravel volume is installed only just before closure, partial clogging of the bed beneath the structure is not expected to be crucial for the performance of the Gravel repository.

9.2.4 Processes that may affect the engineered barrier system during the backfilling and sealing phase

During the backfill and closure of the repository, large amounts of gravel will be transported and deposited in the repository. However, as long as the material has been carefully washed and the amount of dust and fine particles are low the risk for the formation of layers with a lower hydraulic conductivity in the gravel bed is judged to be low.

9.2.5 Processes that may affect the engineered barrier system during the post-closure period

The identified degradation mechanisms during the post-closure period are mainly the same as those during the operational phase of the repository. The debris from the construction, operation and closure periods together with bacteria and algae may clog the pore system of the gravel fill. For the post-closure period, precipitation of minerals may also contribute to the clogging of the pore volume. It may show to be favourable to use rock with the same mineralogical composition as the bedrock.

The following risks can be stated:

- The cage medium will not maintain the designed hydraulic conductivity.
- The concrete base slab will degrade and clog the gravel medium.

9.3 Engineering principles

In Section 9.2 a few processes that may affect the hydraulic properties of the gravel in the hydraulic cage have been presented. In this section means to reduce or avoid the negative effects of these processes are discussed. In general careful handling of materials during construction and operation should be promoted in order to reduce the amount of fine particles and debris in the gravel bed beneath the concrete structure. Further aspects are discussed below.

9.3.1 Choice of hydraulic cage medium

The cage medium shall be designed for the minimum required hydraulic conductivity (10^{-5} m/s or greater) with a satisfactory safety margin. The design should consider the degradation mechanisms discussed in Section 9.2.

The suggested grain size distribution in Section 9.1 can probably be stretched at the lower limit to even finer material. Using an empiric formula by Kennedy et al. (1984) which have been tested on coarse material, the minimum grain size for achieving hydraulic conductivity above 10^{-5} m/s is about 0.01–0.1 mm. In Figure 9-2 a diagram based on the formula by Kennedy et al. (1984) is presented. This means that there is plenty of room for smaller particles in the crushed material. To ensure a comfortable margin to the required lower limit for hydraulic conductivity of 10^{-5} m/s, the smallest sieve size can be set to 16 mm. A wider range of accepted grain sizes will lower the cost for material production as less wastage can be presumed.

9.3.2 Construction of the engineered barriers

The construction of the Gravel repository begins with the foundation for the base slab. This bed of shot rock/gravel will be a part of the hydraulic cage. Drainage systems for the operational period are installed and thereafter the base slab is erected. The identified risk of clogging of the cage medium during the operational phase should be minimised implying that the cage medium must be protected. This protection could probably be accomplished by using removable geo-membranes, pavement and proper drainage systems.

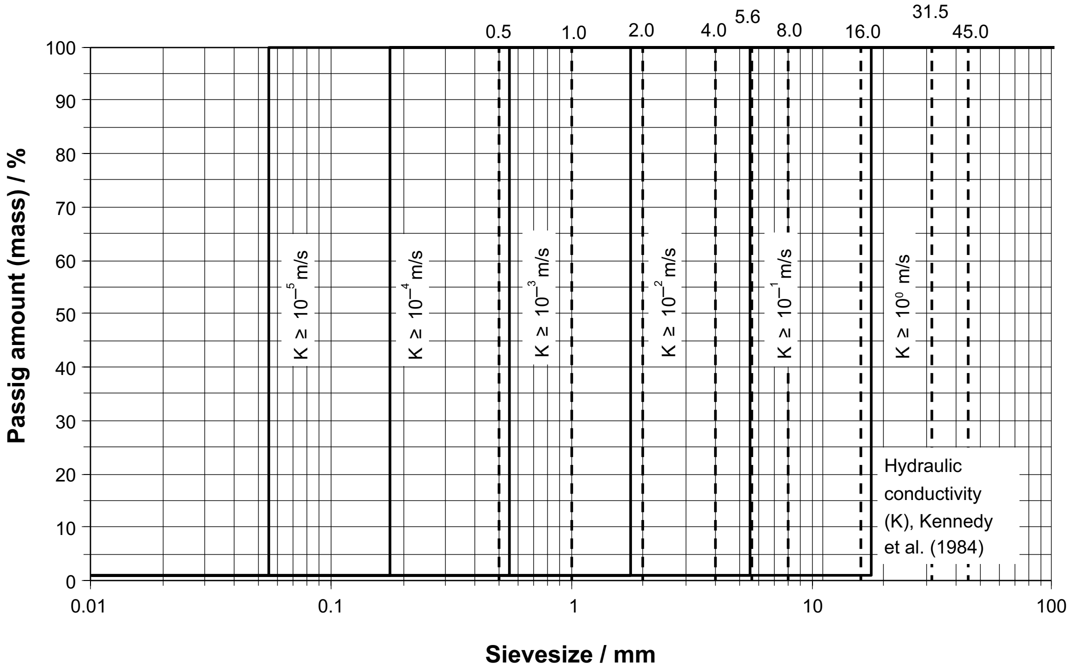


Figure 9-2. *Approximate lower grading limit for 10^{-5} m/s ≤ hydraulic conductivity (K) ≤ 1 m/s for compacted soils. For uncompacted soils, the limits will be transposed to the left along the sieve size axis.*

Due to the nature of the hydraulic cage, which make use of the gradient in hydraulic conductivity between the host rock, the gravel and the waste containers, the waste containers need to uphold a low hydraulic conductivity for as long time as needed to ensure the long-term safety of the repository. If the integrity of the waste containers is compromised at some point during the post-closure phase, the cage material will rather accentuate than dampen the effect of radionuclide release, since it provides a fast transport route.

During operation, the layout presented in Figure 9-1 requires that a temporary radiation shielding is erected around the RWCs, at least for the RWCs containing core components (Section 5.2.2). Provided that the RWCs are sufficiently shielded, or surrounded by e.g. pre-fabricated concrete structures, the work environment during installation and backfilling phases are deemed to be satisfactory.

The RWCs and the cage medium must also be designed to endure the backfill installation process. In particular this calls for a durable exterior of each RWC type and a limitation of the grain size of the medium. Relatively large grain sizes will threaten to damage the RWCs at installation.

The final construction of the hydraulic cage will begin after that all RWCs have been deposited. This part of the construction includes backfilling of the free spaces between the waste containers and the rock with the selected types of gravel. The installation of gravel is proposed to be performed with a system of conveyers at repository level combined with transport vehicles along the access ramp, see Section 9.4.

9.4 Backfilling of the repository

Based on present technology, the installation of gravel includes the following operations, see also Figures 9-3 and 9-4:

1. Crushing of unsorted quarried material. Conducted in situ or at a nearby site.
2. Sieving, washing and mixing of crushed material to prescribed gradation. The cleaning should remove the major part of fines, hence improving (increasing) hydraulic conductivity of the material.
3. Loading of transport vehicle. At this step it would be suitable to moist the cage material with water. This will reduce dust in the tunnels.
4. Vehicle transport.
5. Reloading to the conveyor system. Suggested method is the use of semi trailers with side dumping, since the height of the tunnel is limited. The cage medium is dumped into an intermediate bulk station with a storage capacity suited for optimum use of the transport vehicles and conveyers. At this station it is suitable to wet the cage material to further reduce dust and also to reduce friction between grains. The pre-wetted cage material will reduce settlements induced by later waster saturation of the cavern.
6. Conveyor transport. The conveyers should be agile and easily relocated. For the filling of the caverns it is proposed to use mobile and self propelled conveyers from the reloading station.
7. Unloading conveyer at slope face. The conveyer systems last components will preferably be mobile and have flexible length and thereby be able to control the upper end of the conveyer in three dimensions to cover the complete slope. As the slope advances towards the conveyer the conveyer is retracted to stay in front of the slope. Thereby it is possible to keep the conveyer top close to the slope top as the preceding conveyers are removed one by one.

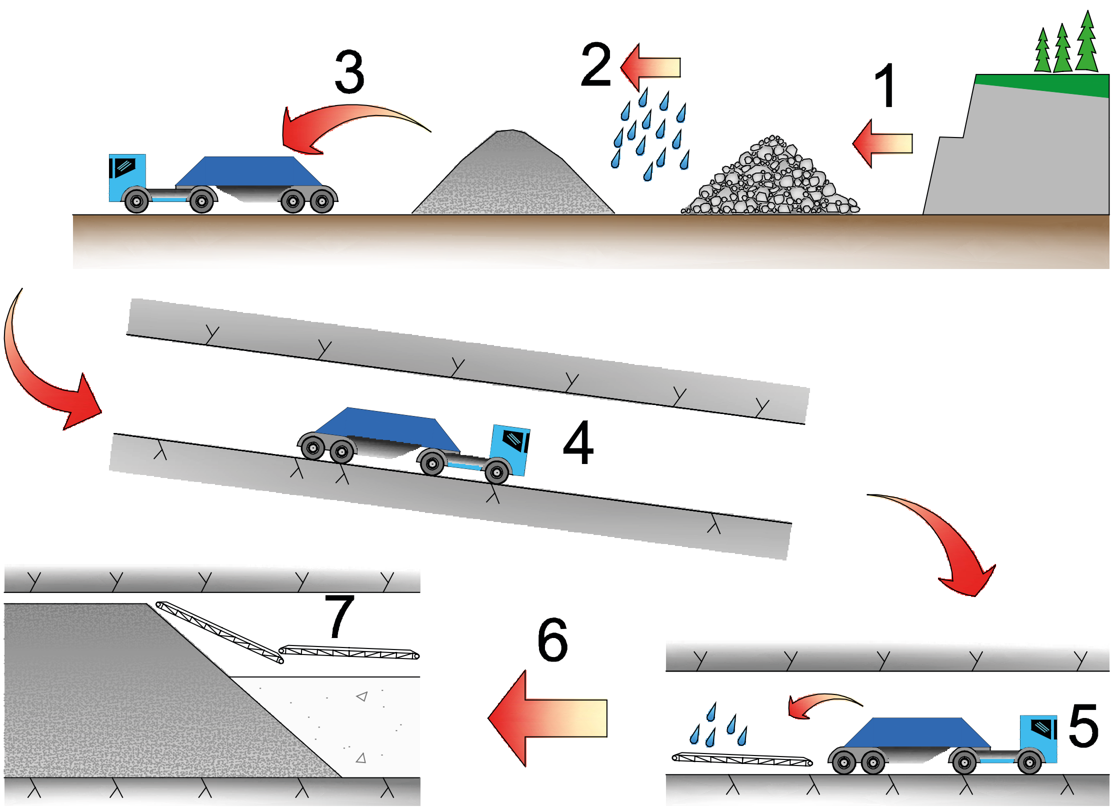


Figure 9-3. *Logistic principles for backfilling a repository cavern with gravel. The proposed installation technique is the use of conveyor belts. These belts will be installed on top of the RWCs, see Figure 9-4.*

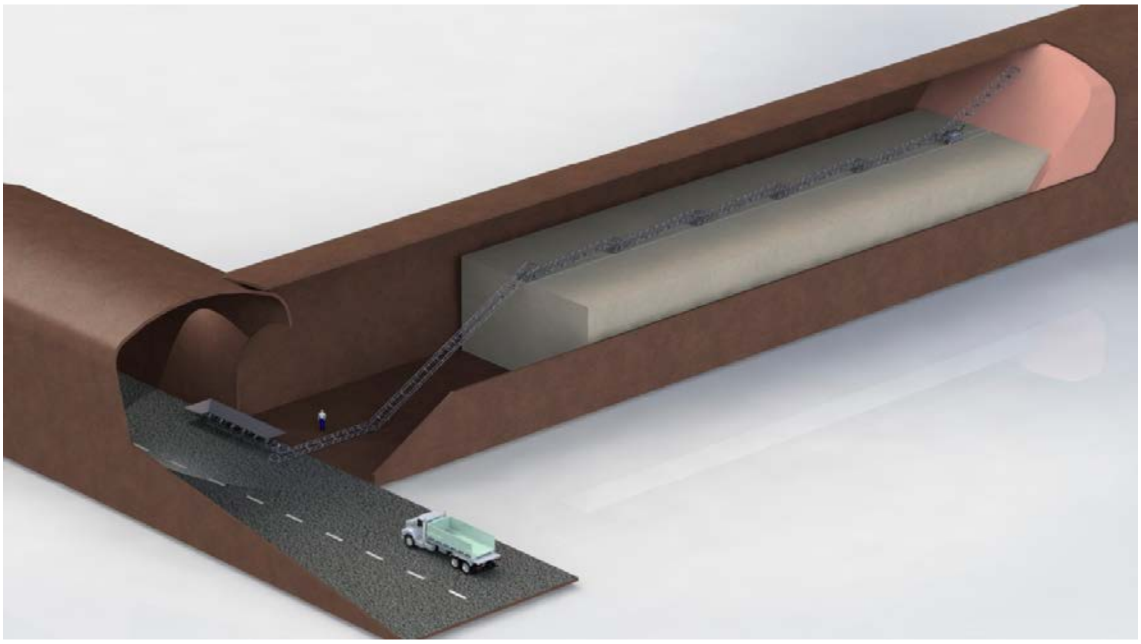


Figure 9-4. *Installation of gravel in cavern with conveyor belts. (Nyblad and Wimelius 2013).*

9.5 Summary and conclusions

In this chapter the characteristics of the Gravel repository was initially presented. This was followed by a description of the processes that could possibly affect the properties of the material in the hydraulic cage. Finally, engineering methods that could be used to reduce the negative effects of these processes was discussed.

From this study, it can be concluded that the main adverse process is clogging of the gravel in the hydraulic cage due to the growth of biological matter or by rock mud or debris from the construction and operational phases. It was thus suggested that the gravel beneath the concrete structure, which is installed during the construction of the repository, should be protected until the time for closure.

It was also concluded that a gravel material with a grain size of 16–32 mm is judged to give the desired high hydraulic conductivity (10^{-5} m/s or greater) and still serve as a practical backfill material from an installation perspective. It was also suggested to use gravel with the same mineral composition as the host bedrock.

Another issue that has been identified is that the waste containers used in the Gravel repository must be stable over the entire operational period of the repository in order to isolate the waste from the freely moving water in the hydraulic cage. In comparison to the other studied concepts for SFL, the Gravel repository will demand higher performances from the RWCs, as they will be subjected to more intensive exposure of groundwater. Each RWC deposited in the Gravel repository must retain its function as a low permeable barrier in the long-term perspective.

10 The Super silo

10.1 General description of the Super silo

The Super silo is a geological disposal concept with the purpose of limiting the release of radio nuclides to the environment by combining multiple engineered barriers. The barriers' functions are to limit the groundwater flow through the waste and to limit the diffusive transport of species from the waste. The concept includes a hydraulic cage constituting of gravel or crushed rock and materials with low hydraulic conductivity and low diffusivity such as concrete and bentonite.

The Super silo consists of a cylindrical double-wall concrete silo with a height of about 40 metres and a diameter of about 35 metres. The repository is planned to be placed in crystalline rock at a depth of 300 to 500 metres. The space between the concrete walls is filled with bentonite. The outer silo is placed on a layer of gravel and the space between the outer silo walls and the rock is also filled with gravel. At closure a lid comprising a concrete-bentonite-concrete combination with the same properties as in the silo walls is placed on the silo. The top of the cavern is then backfilled with gravel.

The inner part of the silo is divided into separate shafts similar to the silo in SFR. The size of each shaft will be approximately 2.8 metres × 2.8 metres to allow for some space between the waste containers and the shaft walls. The inner diameter of the inner silo is about 25 metres. The height of the inner silo is approximately 25 metres, but it can be adjusted to accommodate the required amount of waste. The wall thickness of the concrete silos as well as the bentonite liner are one metre each, the same for the bottom and the lid, Figure 10-1.The drained gravel floor on top of the bedrock is also one metre. Finally, the space between the outer concrete cylinder and the rock is filled with gravel.

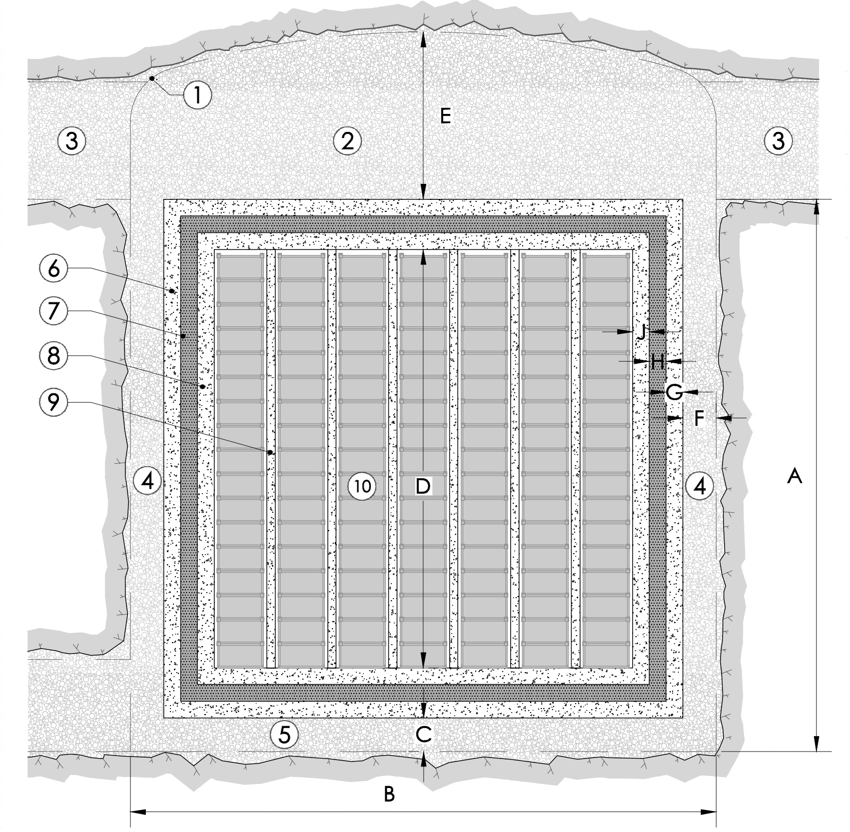


__Figure 10-1.__ Cross-sectional view of the Super silo concept after backfilling. Legend: 1) Theoretical rock cavern contour. 2, 3, 4, 5) Gravel or crushed rock. 6) Reinforced concrete. 7) Bentonite blocks. 8) Concrete. 9) Concrete shaft walls (0.5 m). 10) Waste containers. Approximate dimensions: A = 33 m, B = 35 m, C = 2 m, D = 25 m, E = 5–10 m, F = 2 m, G = 1 m, H = 1 m, J = 1 m.

10.1.1 Main components of the engineered barrier system

The main components of the engineered barrier system are:

- Inner concrete silo: Concrete, thickness 1 metre.
- Bentonite barrier: Thickness 1 metre.
- Outer concrete silo: Reinforced concrete, thickness 1 metre.
- Outer backfill: Gravel, thickness 2 metres.
- Bottom: Drained gravel, thickness 2 metres.
- Top: Gravel, thickness 5–10 metres.

10.1.2 Safety functions of the engineered barriers

The primary safety function of the Super silo is retardation.

This is achieved by a combination of engineered barriers with the following safety functions:

- Low hydraulic conductivity in both the concrete cylinders and the bentonite liner between the concrete cylinders.
- Low diffusivity in both the concrete cylinders and the bentonite liner between the concrete cylinders.
- Strong sorption of radionuclides mainly in the concrete cylinders but also in the bentonite liner.
- High hydraulic conductivity in the hydraulic cage formed by the gravel around the outer concrete cylinder.
- Filtering of colloids in the bentonite liner.

The natural barrier – the bedrock – will contribute to the primary safety function retardation.

10.2 Design considerations

10.2.1 Processes that may affect the engineered barrier system, overview

During all phases of the lifetime of the repository different processes may alter the properties of the materials in the engineered barrier system. Examples of such processes are e.g. leaching of concrete, reactions between concrete and bentonite, and clogging of the hydraulic cage. In Sections 10.2.2–10.2.7 the most important processes are discussed.

10.2.2 Processes that may affect the engineered barrier system during the construction phase

Which degradation mechanisms that are of relevance for the Super silo already during the construction of the repository is to some extent dependent on the choice of construction method and sequence of the installation of the different components of the engineered barrier system.

In the following sections it is assumed that all types of materials except for the backfill on top of the construction are installed during the construction of the repository. This is motivated by that there is a larger potential for material degradation if this method is chosen, than if the material is all installed at the time of backfill and closure (see Section 10.8 for a description of the installation sequence).

Processes that may affect the concrete structures

During the construction of cthe concrete structures in the repository, there is mainly one important process – shrinkage – followed by the formation of cracks during and after the hydration of the concrete, which influences the properties of the concrete barriers. This process is described in Section 7.2.2.

Processes that may affect the bentonite

As mentioned in the introduction of this section, it is foreseen that the bentonite will be installed between the two concrete structures during the construction of the repository. It is not expected that the bentonite will degrade during this process. However, the bentonite must be protected from interactions with the groundwater in order to avoid swelling of the bentonite at this stage.

Processes that may affect the hydraulic cage

As mentioned in the introduction to this section, it is assumed that the gravel will be installed between the outer concrete structures and the bedrock during the construction of the repository. It is not expected that the gravel will degrade during this process. However, care must be taken not to contaminate the gravel with concrete or bentonite during this work because this could reduce the hydraulic conductivity of the gravel bed.

10.2.3 Processes that may affect the engineered barrier system during the operational phase

Potential degradation processes during the operational phase of the repository are mainly caused by the interactions between the barrier material and the groundwater, chemical species present in the groundwater or gases in the repository, mainly carbon dioxide, CO_2. Only a minor direct interaction can be expected between the concrete and the bentonite, since both these materials are expected to be dry during this phase.

Processes that may affect the concrete structures

During the operational phase of the repository, several processes can affect of the concrete barriers. These are mainly related to the interaction between the concrete barrier, the reinforcement bars in the concrete structure and the groundwater, but also the CO_2 in the atmosphere which causes carbonation of the concrete surface. The floor of the concrete structure is also affected by mechanical loads from the waste containers. Finally, the walls of the concrete structure will have to withstand the loads from the grouting around the waste containers.

Many of the processes, which may affect the concrete structures in the Super silo, are also of relevance to the Concrete repository. Please refer to Section 7.2 for details on the following processes:

- Mechanical forces on the barrier walls from the grouting of containers.
- Drying of the concrete.
- Temperature variation.
- Carbonation.
- Chloride ingress.
- Alkali aggregate reactions.
- Metal corrosion.

Besides these processes there are also processes which are unique for the Super silo. These processes are described in the following sections.

Mechanical forces acting on the bottom slabs caused by the stacking of containers

The Super silo consists of two concrete silos in which the waste containers will be stacked to a height of at least 25 metres. The construction, where the outer silo rests on a gravel bed and the inner silo on a bed of bentonite, may give rise to uneven settling of the entire structure, a process which may cause the formation of cracks in the structure. For that reason, stacking of the containers must be distributed evenly in the repository.

Internal forces on the barrier walls from grouting of containers

When the waste containers have been placed in the shafts, the space between the containers will be filled with a grout in order to stabilise the stack of waste containers. During the grouting, the concrete walls will be affected by a hydrostatic pressure from the wet grout. The magnitude of the load depends on the height of casting, the viscosity of the grout and the density. The highest stresses will appear near the bottom and if the stresses get too high the wall might crack. In order to reduce the stresses in the concrete structure, the grouting can be done in steps where grouting is performed at regular intervals when the silo has been only partially filled. This method is used in the silo in SFR today.

Mechanical forces acting on the inner bottom slab caused by uneven settlement of the bentonite foundation

The settlement of the bentonite foundation may induce stresses on the bottom slab. In the case these stresses exceed the tensile strength of the concrete structure, fractures may be formed. For that reason requirements on the deformation properties of the bentonite foundation as well as on the strength of the bottom slab will need to be formulated.

Processes that may affect the bentonite

The most import processes that may affect the bentonite during the operational phase of the repository are caused by the interactions with the groundwater and/or the concrete. Here, interactions with the groundwater may cause an early swelling of the bentonite and an uneven settlement of the concrete structures. However, swelling of bentonite is an expected process and of little concern unless it is very extensive during this early phase of the repository lifetime.

Another process which may affect the properties of the bentonite is caused by interactions between bentonite and concrete in the presence of groundwater. This process may reduce the swelling pressure of the bentonite due to the interactions with the OH^- ions in the concrete pore water and increase the permeability of the bentonite.

For these reasons the bentonite must be protected from intruding groundwater during the operational phase of the repository.

Processes that may affect the hydraulic cage

The main degradation mechanism of the layer of gravel between the outer concrete silo and the bedrock during the operational phase of the repository is clogging caused by crack minerals or biologic matter. Both these processes are dependent on groundwater being present and can thus be avoided if the groundwater is prevented from entering the repository. Clogging of gravel beds is discussed further in Section 9.2.

10.2.4 Processes that may affect the engineered barrier system during the backfilling and sealing phase

The most important processes which may affect the barriers system during the backfilling and sealing phase is crack formation in the lid of the structure caused by careless backfilling of the volume on top of the silo. Forces caused by resaturation of the rock vault, swelling of bentonite etc are treated in Sections 10.2.5–10.2.7. The backfilling and sealing phase is too short for any chemical processes to have a significant impact on the properties of the engineered barrier materials.

Processes that may affect the concrete structures

As mentioned above, the only degradation mechanism of any possible significance during the backfilling and sealing phase is cracking of the lid of the concrete structure due to careless handling of the backfill material.

Processes that may affect the bentonite

No significant degradation of the bentonite is expected during the short backfill and sealing phase.

Processes that may affect the hydraulic cage

No degradation of the hydraulic cage is expected during the backfill and sealing of the repository.

10.2.5 Processes that may affect the concrete structures during the post-closure phase

During the post-closure phase the properties of the materials in the engineered barriers will possibly develop over time. Even though these processes are very slow in ordinary terms, they may in the long-term affect the properties of the concrete structures in the Super silo.

Several of the processes which may affect the concrete structures in the Super silo during the post-closure period, are also of relevance to the Concrete repository. Please refer to Section 7.2 for details on the following processes:

- Mechanical forces caused by groundwater pressure.
- Mechanical forces caused by rock movements.
- Mechanical forces from processes inside the concrete structure.
- Leaching of concrete.
- Chloride ingress.
- Sulphate attack.
- Reactions with other types of salts.
- Alkali aggregate reactions.
- Metal corrosion.
- Degradation of organic material.
- Gas formation.
- Freezing.

Besides these processes, also other processes which are unique for the Super silo may affect the properties of the concrete structures during the post-closure phase.

Mechanical forces on the concrete structures

During the post-closure phase the concrete structure will experience mechanical forces of different magnitudes and origin. The impact of the forces on the concrete structures is not only dependent on the magnitude of the force but also on to which extent the concrete has degraded, i.e. the time after closure, and whether the forces are internal, e.g. a gas pressure, or external, e.g. the groundwater pressure.

In this section the different mechanical forces that will act upon the concrete structures will be discussed. This will then form the basis for the dimensioning of the Super silo, as well as choice of materials and design strategy which is further discussed in Sections 10.3–10.5.

Saturation and build up of water, gas and swelling pressure – Prerequisites

During the resaturation of the repository water will slowly fill the rock vault and saturate the porous media in the engineered barriers. Of importance for the integrity of the engineered barrier system are both the external force from the groundwater pressure acting on both concrete structures, and the pressure from the swelling of the bentonite. The latter will exert an internal pressure on the outer concrete structure and an external pressure on the inner concrete structure. However, since the inner concrete structure can be treated as one concrete monolith since the waste is stabilized in the RWCs using grout, the inner concrete structure is not treated further in this work.

In Section 10.5 three different design strategies for the choice of bentonite type and quality are presented. The choice of design strategy will mainly affect the swelling pressure of the bentonite, but this will have a considerable effect of the forces that will act upon the concrete structures. In Table 10-1 the properties of the bentonite for the different design strategies are summarised.

In order to estimate the forces that will act upon the concrete structures a reference evolution for the repository, which is similar for all design strategies, have been identified. The reference evolution involves the following phases, which are elucidated in more detail below:

1. Initial state: Evolution step 0.
2. Gravel is saturated from bottom to top, with a build up of water pressure: Evolution step 1.
3. Concrete in outer silo is saturated.
4. Gas generation from corrosion of reinforcement in outer silo begins.
5. The bentonite is saturated, swells and homogenises: Evolution step 2.
6. The inner silo and the waste is saturated, full hydrostatic pressure in the bentonite: Evolution step 3.
7. Gas generation from anaerobic corrosion of metals and microbial degradation of any organic materials: Evolution step 4.

Of these, it has been recognised that the most important evolution steps are evolution steps 1, 2 and 3, explained in more detail below:

1. In evolution step 1, the rock cavern outside the outer concrete cylinder is entirely filled with water but the water pressure will only affect the outer silo. No water has yet entered the concrete structures or the bentonite.
2. In evolution step 2, the bentonite has been completely saturated and exerts its full swelling pressure on the concrete structures.
3. In evolution step 3, the hydrostatic pressure in the bentonite has reached the same level as in the rock cavern.

The hydrostatic pressure exerted on the Super silo is bound to the depth at which the structure is placed in the rock. At 500 metres depth the hydrostatic pressure is approximately 5 MPa.

In the following section the corresponding forces for the three different design strategies acting upon the outer concrete structure during evolution steps 1–3 have been calculated.

Calculations

The initial calculations involved the identification of a number of relevant load cases representing combinations of design strategies and evolution steps. With three design strategies and three evolution steps a total of nine load cases were identified, Table 10-2.

Table 10-1. Assumed swelling pressure for the described design strategies.

Design strategy	Swelling pressure Bottom bed (MPa)	Swelling pressure between walls and at roof (MPa)
1	0.4 (0.2–0.5)	0.4 (0.2–0.5)
2	4 (2–7)	0.5
3	4 (2–7)	4 (2–7)

Table 10-2. The load cases (LC) included in this study.

Load case	Design strategy	Evolution step No:	Swelling pressure (Bottom bed within brackets) (MPa)	Hydraulic pressure gradient over outer silo (MPa)	Hydraulic pressure gradient over inner silo (MPa)
LC1	1	1	0	5	0
LC2	1	2	0.4	0	5
LC3	1	3	0.4	0	0
LC4	2	1	0	5	0
LC5	2	2	0.4 (4)	0	5
LC6	2	3	0.4 (4)	0	0
LC7	3	1	0	5	0
LC8	3	2	4	0	5
LC9	3	3	4	0	0

The following assumptions were made in the calculations:

- The inner concrete structure was treated as a concrete monolith with grout-filled containers and grout also filling all spaces between the concrete structure and the waste containers. The inner concrete silo can thus not be deformed regardless of the magnitude of the forces acting upon it.
- The bentonite swells homogeneously and no pressure gradient occurs in the bentonite.
- The fresh bentonite between the two concrete walls does not give any support to the outer concrete structure in order to balance the external forces from the groundwater.
- The pressure from the gravel surrounding the Super silo is not included in these calculations. This can be motivated by that it exerts a very low pressure on the concrete structure in comparison with the hydrostatic pressure from the groundwater.
- No effects from the bottom or top slabs were considered.
- The diameter of the outer concrete cylinder is 35 metres.

The stresses in the outer concrete cylinder have been calculated according to Equations 10-1 to 10-4. In these equations *x* and *y* represent the radial and tangential stresses when the cylinder is loaded from both the inside and the outside, whereas *z* and *q* represent radial and tangential stresses when the structure is loaded only from the outside.

$$\sigma_t = \frac{1}{k^2-1}\left(p_i\left(\left(\frac{R_y}{r}\right)^2+1\right)-p_y\left(k^2+\left(\frac{R_y}{r}\right)^2\right)\right) \qquad \text{10-1}$$

$$\sigma_r = -\frac{1}{k^2-1}\left(p_i\left(\left(\frac{R_y}{r}\right)^2-1\right)+p_y\left(k^2-\left(\frac{R_y}{r}\right)^2\right)\right) \qquad \text{10-2}$$

$$\sigma_t = -p_y\frac{k^2+\left(\frac{R_y}{r}\right)^2}{k^2-1} \qquad \text{10-3}$$

$$\sigma_r = -p_y\frac{k^2-\left(\frac{R_y}{r}\right)^2}{k^2-1} \qquad \text{10-4}$$

In the equations, R_y is the outer radius and R_i is the inner radius of the concrete structure, p_i is the pressure above atmospheric pressure from the inside and p_y from the outside. The radial stress is presented with σ_r and the tangential stress with σ_t. A positive value represents a tensile stress and a negative value a compressive stress respectively. k is the quotient between R_y and R_i. In the calculations the stresses presented are obtained in the centre of a one metre thick wall in the centre of the cylinder.

In Table 10-3 the radial and tangential stresses obtained in a section of the wall for the different load cases in Table 10-2 are presented with values from Equations 10-1 to 10-4. LC1, LC4 and LC7 are identical for all three design strategies, since there is no influence from the bentonite. The results are thus only presented for design strategy 1, corresponding to LC1.

Evolution step 1

When the gravel outside the outer concrete structure has been fully saturated with water the concrete structure for all 3 design strategies will experience very high tangential compressive stresses as shown by the high value of σ_t for LC1 in Table 10-3. Since the bentonite has not yet been saturated, no internal pressure can compensate for the very high external forces and as a consequence the tangential compressive stresses in the outer cylinder are very high, –87.5 MPa.

Evolution step 2

When also the bentonite has been completely saturated and exerts its full swelling pressure – corresponding to LC2, LC5 and LC8 – strong internal forces will to some extent balance the external forces caused by the hydrostatic pressure from the groundwater. A comparison between Table 10-1 and Table 10-3 show that the higher the swelling pressure of the bentonite, the lower the tangential compressive stress in the outer concrete cylinder after that the bentonite has reached its maximum swelling pressure. The effect on σ_r is present but less pronounced.

Evolution step 3

When the maximum hydrostatic pressure from the groundwater has been reached also in the bentonite corresponding to LC3, LC6 and LC9 the stress in the outer concrete cylinder switch from being compressive to tensile. This is especially true for LC9 where the tangential tensile stresses are very high. Yet again the radial stress are also affected but to a lesser extent.

Summary and discussion

The calculations presented above show that the compressive stress obtained during evolution step 1 for all design strategies are significantly higher than the compressive strength for ordinary concrete after 28 days. As an example, the characteristic compressive strength for a C60/75 according to BBK 04 is 57 MPa when long-term loading is considered.

This is also true for evolution step 2 for design strategy 1 and 2 where a bentonite with a rather low swelling pressure is used between the walls of the two concrete cylinders. For design strategy 3 the compressive stress during evolution step 2 is lower than the characteristic strength of the concrete, due to the high internal swelling pressure from the bentonite, which balances the high external forces from the groundwater pressure.

For evolution step 3, i.e. where also the bentonite experiences the full hydrostatic pressure, the stress in the outer concrete cylinder becomes tensile for all design strategies. This is particularly evident for design strategy 3 where the tensile stress is more than 60 MPa. This can be compared to the tensile strength in ordinary C60/75 concrete which can reach approximately 5 MPa. However,

Table 10-3. Calculated stress for a cylinder wall with a diameter of 35 metres for the different load cases presented in Table 10-2. LC4 and LC7 are identical to LC1 and hence omitted from the table.

	LC1	LC2	LC3	LC5	LC6	LC8	LC9
Outer pressure (MPa)	5	5	5	5	5	5	5
Inner pressure (MPa)	0	0.4	5.4	0.5	5.5	4	9
Position from centre (m)	17	17	17	17	17	17	17
σ_t (MPa)	–87.5	–80.9	1.6	–79.2	3.2	–21.5	61
σ_r (MPa)	–2.6	–2.8	–5.2	–2.9	–5.2	–4.5	–6.9

the characteristic design strength is usually only between 1 and 3 MPa depending on what type of concrete that is used. The concrete type C60/75 has a characteristic tensile strength of 2.95 MPa, when long-term effects are included.

To conclude, these calculations have shown that the outer concrete cylinder of the Super silo will at some time during the resaturation of the repository experience compressive or tensile stresses, which by far will exceed the compressive or tensile strength of ordinary C60/75 concrete.

In order to handle this, two options are available: Either to change the dimensions of the Super silo or to use another type of concrete. Choice of concrete type is discussed in Section 10.4.1 and calculations showing the possibilities to handle the high stresses by means of reducing the dimensions of the Super silo are discussed in Section 10.4.2.

Rock movements

Rock movements can affect the concrete structures if they are large enough. However, the layers of gravel and bentonite surrounding the concrete structures may protect the concrete structures from the effect of such movements.

Pressure from the backfill material and gravel

The pressure from the outer gravel and the backfill is regarded as negligible in comparison with the groundwater pressure and the pressure from the swelling of the bentonite and will not be considered here.

Groundwater pressure

After that the cavern has been backfilled with gravel, the groundwater will, with time, fill the voids. When the cavern is filled with water and in equilibrium with the rock the pressure that will affect the outer silo is equal to the hydrostatic pressure, which with the planned repository depth of about 500 metres below ground will correspond to approximately 5 MPa.

Earlier in Section 10.2.5 calculations of the stress caused by the hydrostatic pressure showed that the tangential stress in the outer concrete structure is very high during the period when the hydraulic cage has been saturated but prior to that the maximum swelling pressure of the bentonite has been reached.

Swelling of waste

In SFL the main process that could cause internal forces by swelling of the waste is corrosion of metals. During the process an internal pressure will build up around the metallic parts due to fact that the volume of the corrosion products is larger than the volume of the pristine metal. The long-term effect of this process is that the internal pressure may exceed the tensile strength of the concrete and consequently to that cracks are formed in the concrete structure unless the corrosion products are dissolved and removed. Metal corrosion is discussed further in Section 7.2.

Gas formation

Gas can be formed either as a consequence of metal corrosion or by the degradation of organic material. The formation of gas in the repository can in the worst case lead to the build-up of pressure, which might lead to a cracking of the repository concrete structure.

Chemical interaction with bentonite

When concrete and bentonite are in contact, transport of ions between the concrete and the bentonite may occur, see for instance Höglund (2001). Even though the effects of these interactions are of more concern to the bentonite, whose swelling pressure can be reduced through the interaction with alkaline water from the concrete, ions diffusing from the bentonite may cause mineralogical alterations of the cement phases.

10.2.6 Processes that may affect the bentonite liner during the post-closure phase

In the Super silo, the bentonite liner is entirely enclosed within the concrete structure. For that reason it is expected that processes such as piping and erosion can be neglected. Instead, changes in the properties of the bentonite which are caused by the interactions with the cement buffered groundwater will dominate during this phase. Processes which may affect the bentonite during the post-closure phase are also discussed in Section 8.2.5.

10.2.7 Processes that may affect the hydraulic cage during the post-closure phase

The most important process that may affect the hydraulic cage during the post-closure phase is clogging by rock mud or by biological matter. These processes are discussed in Section 9.2.

10.3 Engineering principles, overview

In Section 10.2 a number of processes that could affect the properties of the engineered barriers in the Super silo were presented. In the following sections different methods related to choice of material, design and construction of the engineered barrier system that could be used to reduce or eliminate the effect of these processes on the long-term properties of the engineered barrier system are discussed.

10.3.1 Concrete structures

As shown in Figure 10-1, the Super silo constitutes two concrete barriers, the outer and the inner silo with a layer of bentonite in between. The functions of the silos are to act as a barrier with low diffusivity and permeability but also to contain the bentonite. For this reason the silos have to be constructed so that cracks are not formed and that they can withstand both internal and external forces such as groundwater pressure, pressure from grouting as well as from the swelling of the bentonite.

As discussed in Section 10.2 many of the processes that may affect the concrete structures are dependent on the presence of groundwater. For that reason it is essential that the concrete structures, and all components within, are protected from contact with groundwater prior to sealing and closure to reduce the risk of e.g. corrosion of the reinforcement bars during the operational phase of the repository. Strategies for this are discussed in Section 10.7.

In order to mitigate the effects of the processes most active during the post-closure phase the composition of the concrete and the design and dimensions of the concrete structures have to be carefully evaluated. Aspects related to concrete composition are discussed in Section 10.4.1 and design issues in Section 10.4.2.

10.3.2 Bentonite

As shown in Figure 10-1, the Super silo comprises a layer of bentonite sandwiched between two concrete silos. The specific function of the bentonite layer is to provide very low hydraulic conductivity and thus reducing the rate of water transport through the engineered barrier system. In order to ensure that the function of the bentonite can be maintained over the entire operational life of the repository it is essential that the swelling pressure of the bentonite can be maintained.

In Section 10.2 processes that could affect the properties of the bentonite were discussed. These processes can either cause a physical alteration of the bentonite but also a chemical change of the material through interactions with the groundwater or the pore water in the concrete structures.

In order to mitigate the effects of these processes careful choices on type of bentonite and method for its manufacturing to give the desired shape and dry density have to be made. This is discussed in Section 10.5.

10.3.3 Hydraulic cage

As shown in Figure 10-1, the super silo constitutes a layer of gravel sandwiched between the outer silo and the rock wall. The function of this layer of gravel is to act as a hydraulic cage through which a majority of the groundwater that enters the repository rock vault will be transported.

In order to ensure the long-term properties of the hydraulic cage it is essential that the gravel is not clogged by minerals, debris or biological matter during the entire operational life of the repository. This is discussed further in Section 10.6.

10.4 Engineering principles: Concrete structures

Many of the processes discussed in the previous sections can be handled by means of a correct choice of concrete composition and fabrication method for the concrete structures. In the following sections different opportunities are discussed. In Section 10.4.1 the influence of the composition of the concrete is discussed. In Section 10.4.2 construction methods such as the use of cooling and other aspects are treated.

The most crucial issue regarding the design of the Super silo is related to the dimensions of the silo. In Section 10.2.5 it was shown that the magnitude of external and internal forces at repository depth will restrict the dimensions of the concrete silos. In Section 10.4.3 the influence of the dimensions of the concrete structures on their ability to withstand the mechanical forces discussed in Section 10.2.5 is evaluated. Further details are presented in SKBdoc 1415647.

10.4.1 Composition of the concrete

Much of what was said concerning the composition of the concrete in Section 7.3.1 can also be applied to the Super silo and will not be discussed further in this section.

However, two processes are unique for the Super silo, interactions between bentonite and concrete and the high stresses in the outer concrete cylinder caused by the hydrostatic pressure from the groundwater and the swelling of the bentonite.

In order to handle these processes two possibilities have been identified: the use of low-pH concrete and High Performance Concrete, HPC.

Low-pH concrete

As a mean to reduce the negative effect on the bentonite's properties from interaction with alkaline pore water a so-called low-pH concrete can be used. A low-pH concrete contains additives which reduce the amount of portlandite in the concrete and hence the pH in the pore water.

However, low pH concrete has a significantly larger shrinkage than ordinary Portland cement mixes and also the long-term properties of such materials are less well known. Further studies are required before a low-pH concrete can be considered as a safe and reliable material in such repository constructions.

High performance concrete

According to the calculations presented in Section 10.2.5 the outer concrete cylinder has to withstand a compressive stress of at least 90 MPa. This can be compared with the design compressive strength of an ordinary concrete which usually does not exceed 60 MPa. As an example the design compressive strength for a C60/75 concrete is 57 MPa.

There are two possible solutions to this problem, either to reduce the diameter of the silo or to use a High Performance Concrete, HPC.

A HPC is defined as a concrete with a higher strength and durability than ordinary concrete. To increase the compressive strength, pozzolanic mineral additives such as silica fume, fly ash or slag can be added. These additives react with the calcium hydroxides in the concrete and produce a higher amount and calcium silicate hydrates, which is the main strength formation in hydrated cement. With a HPC it is possible to increase the characteristic compressive strength significantly.

10.4.2 Construction of the concrete structure

Besides choosing the most optimal composition of the concrete the casting process is also very important for the final properties of the concrete structure. In Section 7.3.2 constructive aspects regarding the concrete repository were discussed. These issues are valid also for the Super silo and the reader is therefore referred to that section for details.

10.4.3 Dimensioning of the outer concrete cylinder

As was shown in Section 10.2.5 the outer concrete cylinder will experience very high tensile and compressive stresses during the different evolution steps of the repository.

In this section the effect of changes in the dimensions, i.e. the diameter of the outer concrete cylinder of the Super silo is discussed. As a basis for this discussion calculations based on the Finite Element Method, FEM, presented in detail in SKBdoc 1415647 have been performed.

Details of the calculations

The calculations were done using the program ADINA. The structure was modelled as a 2D axisymmetric structure and also included the bottom and the top slabs of the outer concrete cylinder. The calculations comprised design strategies 1 and 3 (Table 10-1) for evolution step 1, 2 and 3 (Section 10.2.5). Design strategy 2 was not included due to the similarities to the other two. The inner cylinder was handled as a monolith that could not move or deform.

Four FEM models were constructed and analysed:

FEM1: FEM1 corresponds to LC1 (Table 10-2). In this model the bentonite is also assumed to withstand some of the deformation caused by the hydrostatic pressure from the groundwater. The properties of the bentonite are assumed to be the same as of a single bentonite block. However, due to gaps between the blocks this scenario is not likely to be valid for the walls but may be valid for the top and bottom slab.

FEM2: In FEM2 the analysis is similar to that of FEM1 but the influence of the bentonite is not included. The actual contribution of the bentonite is not known so the true result should be between the two models.

FEM3: FEM3 corresponds to LC3 (Table 10-2)

FEM4: FEM4 corresponds to LC9 (Table 10-2)

The analysis was done on seven sections on the structure, see Figure 10-2. Section 7 corresponds to the structural component studied in the simplified analysis in Section 10.2.5. The load from the gravel was not considered due to its small impact resulting in symmetry between the top and bottom slabs.

Results

In this section the most important results from the FEM-calculations presented in their entirety in SKBdoc 1415647 are briefly summarised.

FEM1

In Section 3 and 5, tensile stresses of about 15 MPa for a radius of 16 metres and 10 MPa for a radius of 7 metres were obtained. Both these values exceed the tensile strength of a standard C60/75 concrete.

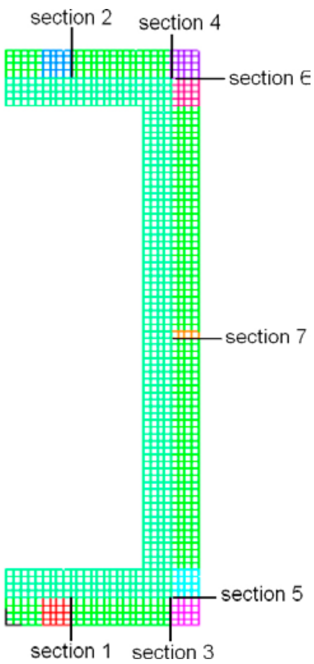


***Figure 10-2.** The 2D axisymmetric structure used for the models and the seven sections (SKBdoc 1415647).*

No tensile stress was obtained in Section 7 and in the bottom and top slabs the highest stress obtained was approximately 2.5 MPa for a radius of 7 metres.

A compressive stress in Section 3 and 5 of about 35 MPa was obtained for a radius of 16 metres.

FEM2

In the the top and bottom slabs tensile stresses of about 350 MPa for a radius of 16 metres and 50 MPa for a radius of 7 metres were obtained.

The compressive stresses in the top and bottom slabs as well as in the corners reached about 450 MPa for a radius of 16 metres and 75 MPa for a radius of 7 metres.

In Section 7 the compressive stress was about 90 MPa for a radius of 16 metres, 50 MPa for a radius of 9 metres and 35 MPa for a radius of 7 metres, respectively.

FEM3

Tensile stresses in the top and bottom slabs of about 35 MPa for a radius of 16 metres and 7 MPa for a radius of 7 metres were obtained.

In the corner the tensile stresses are about 35 MPa for a radius of 16 metres and about 5 MPa for a radius of 7 metres respectively.

In Section 7 the highest tensile stress was about 7 MPa with a radius of 16 metres and below 3 MPa when the radius is 7 metres.

No compressive stresses were found in the calculations.

FEM4

In the top and bottom slabs tensile stresses of about 30–35 MPa for a radius of 16 metres and 10–25 MPa for a radius of 7 metres were obtained. Both these values exceed the tensile strength of a standard C60/75 concrete.

The compressive stresses were lower than the compressive strength for ordinary concrete in the entire structure.

Summary and discussion

In this section calculations of the critical stresses for four different load cases on the Super silo have been summarised. The radius of the outer concrete silo is taken to be between 7 and 16 metres in the parametric study.

The calculations have shown that the stresses in the outer concrete cylinder with a diameter of 16 metres in most of the cases by far exceed the strength of standard C60/75 concrete. The most critical part of the concrete cylinder has been shown to be the connection between the bottom and top slabs and the cylinder wall. In order to balance the compressive stresses caused by the hydrostatic pressure during evolution step 1, well packed high density bentonite blocks have to be used between the concrete structures as in FEM1. If the bentonite is less well packed as in FEM2 the compressive stresses will cause the outer concrete cylinder to collapse.

The tensile stresses reach their highest values when the maximum hydrostatic pressure has been reached also in the bentonite, corresponding to FEM3 and FEM4. For both these design strategies the tensile stresses exceed the tensile strength of a standard C60/75 concrete even if the radius is reduced to 7 metres.

In conclusion, the dimensions on the Super silo have to be reduced significantly to withstand the stresses obtained during the different evolution steps. The calculations show that if the radius of the outer concrete cylinder is reduced to 7 metres it should be possible to construct a structure in accordance to design strategy 1 and possibly also design strategy 2. However, design strategy 3 seems to be close to impossible due to the high tensile stresses in evolution step 3.

However reducing the radius of the concrete silos will have a strong impact on the amount of waste that can be disposed of in the silo. If the radius of the outer concrete silo is reduced to 7 metres, the volumes of the outer and inner concrete cylinders are reduced to about 16% and 10% respectively compared with a radius of 16 metres. Consequently a large number of small silos have to be constructed. The possible influence of the dimensions of the waste containers has not been considered.

10.5 Engineering principles: Bentonite barrier

The design of the Super silo is a complex task due to the interactions between the different barrier components. The most critical parameter is probably the type of bentonite, its methods of fabrication and installation which may call for the use of bentonite with different properties and the use of different methods of installation in different parts of the structure. Once a decision on the choice of bentonite has been made, the requirements on the properties of the concrete structures will become clearer.

The following three design strategies for the bentonite barrier were identified in Section 10.2.5 and are further described below:

1. Design the bentonite barrier so that a relatively low swelling pressure that can be handled by both inner and outer concrete structure is developed. This results in a hydraulic conductivity in the order of 10^{-10} m/s for a groundwater salinity of 1%.
2. Design the bentonite barrier so that the inner concrete structure can withstand the swelling pressure as the outer concrete structure will break.
3. Design the bentonite with as high density as can be achieved. This results in a low hydraulic conductivity, in the order of 10^{-13} m/s, and a swelling pressure in the order of 7–10 MPa for a salinity of 1%. For this alternative it is assumed that both the inner and the outer concrete structures break and the bentonite is the only remaining barrier.

10.5.1 Design strategy 1: Low bentonite swelling pressure

Design strategy 1 implies that the bentonite barrier is designed so that a relatively low swelling pressure is developed, that can be handled by both the inner and the outer concrete structure. This results in a hydraulic conductivity in the order of 10^{-10} m/s for a groundwater salinity of 1%. It should be noticed that this alternative differs from the basic design, Section 10.1, and that is has been developed with the aim of providing a solution which puts less demands on the properties and dimensions of the concrete structure.

Slot between the walls of the inner and outer silos

The space or slot between the two concrete cylinders will be filled with pure bentonite such as granules and extruded and compacted pellets. Experience is available from the SFR silo (Pusch 2003). These materials together with different bentonite qualities can be used as a toolbox for reaching intended density, hydraulic conductivity and swelling pressure. There are a number of concerns related to the installation of the bentonite which will need to be studied further such as achieving a good homogeneity, avoiding dust problems and quality control.

Bottom bed

The design of the bottom bed is the most challenging since very good resistance against deformation will be required in order to support the weight of the inner silo while still providing a low swelling pressure. The following alternatives for the bottom bed will be treated in this section:

1. Mixture of bentonite and sand or crushed rock.
2. Bentonite granules or pellets.

It should be pointed out that in this study the practical aspects of casting the concrete structure on a bottom bed consisting of bentonite or a mixture of bentonite and a non-swelling material are not considered and have to be investigated further. Methods must be developed to protect the bentonite from the wet concrete including the use of e.g. a geotextile or similar or to install a prefabricated bottom of the inner silo.

Bottom bed consisting of mixtures of bentonite and crushed rock or sand compacted in situ.

This alternative yields both mechanical stability and reasonably low hydraulic conductivity. It has been used for the silo in SFR and has been an alternative for backfilling tunnels in the Spent Fuel Repository. There is a fair amount of experience on these types of materials and it has been proven that it is technically feasible to install the material as a bottom bed for the SFR silo (Pusch 2003). So far the deformations of the bottom bed in the SFR have been small.

The bottom bed of the SFR silo consists of a bentonite/sand mixture with the proportions 10/90. The experiences from compaction of the 10/90 material shows that close to 100% compaction degree can be achieved using large roller compactors, corresponding to an average dry density of 2,190 kg/m^3 (Pusch 2003).

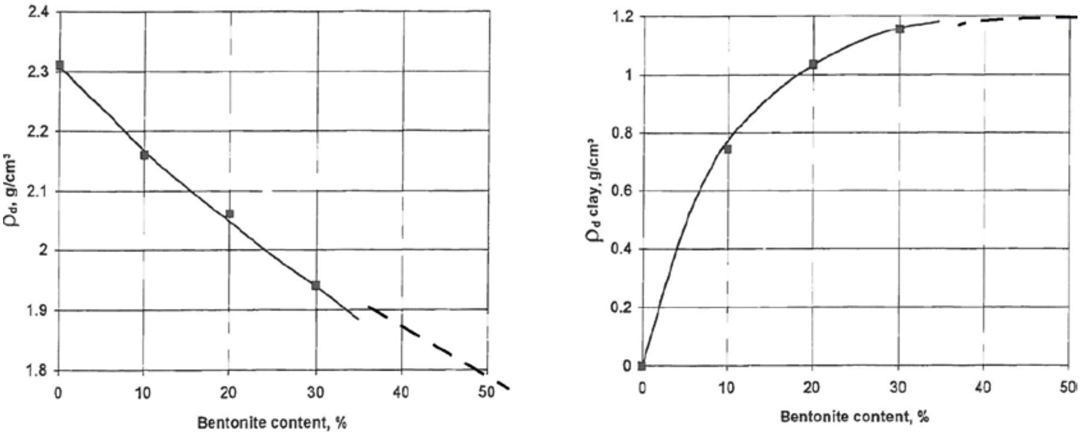


***Figure 10-3.** Dry density (left) and bentonite density as a function of bentonite content at 100% compaction degree (100% compaction degree, modified Proctor compaction).*

It is assumed that 100% compaction degree can also be achieved for horizontal layers of mixtures with 30% bentonite. Hydraulic conductivity for mixtures with 30% bentonite have been measured where the salinity of the saturating water was 1.2% (50% NaCl and 50% CaCl). Figure 10-4 shows hydraulic conductivity as a function of dry density (Johannesson et al. 1999). The large influence of salt in the percolating water is obvious. For salinities of 1.2% and a dry density of 1,940 kg/m^3, the hydraulic conductivity is K ≈ $1.0 \cdot 10^{-11}$ m/s (extrapolation). At 90% compaction degree, the conductivity is K ≈ $2.0 \cdot 10^{-10}$ m/s 90% Proctor (1,750 kg/m^3).

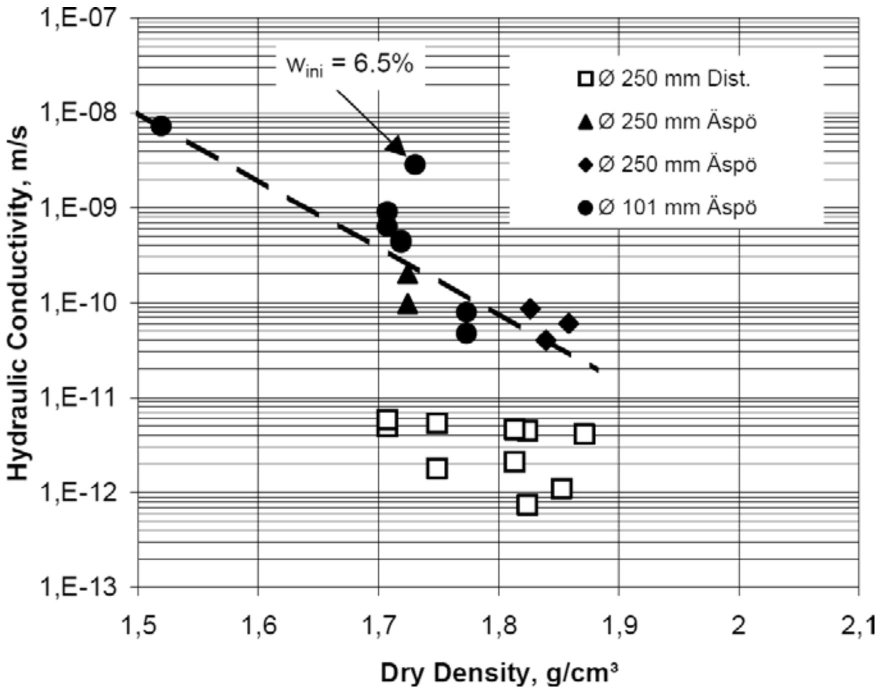
Swelling pressure for mixtures has not been measured as extensively as the hydraulic conductivity. A literature survey (Johannesson et al. 1999, Johannesson and Nilsson 2006, Johannesson 2005) shows that the swelling pressure is probably in the range σ_s ≈ 2 MPa with a dry density of 1,900 kg/m^3, but it rapidly decreases with decreasing density.

Bottom bed consisting of high quality bentonite granules, pellets or powder

As an alternative to a mixture of bentonite and a non-swelling material such as crushed rock or sand, bentonite granules or powder pellets can be used to form the bottom bed. As for the mixture-alternative it must be ensured for a pure bentonite bed that it is compressed and stable enough to withstand the forces from the inner silo when filled with waste and grout.

SKB has extensive experience in the use of pure bentonite but so far no construction has been erected on a bed of compacted bentonite granules, pellets or powder. Great efforts are therefore expected to be required in order to prove the feasibility of this method. It is though expected that pure high quality bentonite (e.g. MX-80) can be compacted in place.

Hydraulic conductivity and swelling pressure are well known for MX-80 at different densities. At the assumed dry density of ρ_d = 1,300 kg/m^3 the hydraulic conductivity K ≈ $1.0 \cdot 10^{-12}$ m/s and the swelling pressure σ_s ≈ 700 kPa. At a dry density of ρ_d = 1,200 kg/m^3 the hydraulic conductivity K ≈ $3.0 \cdot 10^{-12}$ m/s and the swelling pressure σ_s ≈ 500 kPa.



Figur 10-4. *Relation between hydraulic conductivity and dry density for two mixtures of bentonite and crusched rock. Unfilled symbols represent tests performed with destilled water. Filled symbols represent tests performed with 1.2% salinity.*

10.5.2 Design strategy 2: Bentonite blocks in bottom and lid and pellets between walls

This design strategy implies that bentonite blocks are used in bottom and lid and with pellets in the wall.

Bentonite blocks in the bottom bed and on top of the silo

The density of the blocks and the block filling degree can be adapted so that the final density in average is between 1,900 and 2,000 kg/m^3 after water saturation which corresponds to a dry density of ρ_d = 1,410–1,560 kg/m^3. This will give a hydraulic conductivity of about K ≈ 1.0–3.0·10^{-13} m/s and a swelling pressure of $\sigma_s \approx$ 2,000–7,000 kPa. At this high density the influence of the groundwater composition on hydraulic conductivity and swelling pressure is small.

The main challenge is that the inner silo will rest on the bentonite blocks that need to be mechanically stable for the duration of the operational period. The feasibility of this method needs to be investigated.

Slot between the walls of the inner and outer silos

This is managed in the same way as described for design strategy 1 and is not foreseen to be as challenging as the installation of the bottom bed.

10.5.3 Design strategy 3: High density bentonite blocks

This design strategy implies that high density bentonite blocks are placed in the entire volume between the two concrete structures and corresponds to the basic design shown in Figure 10-1.

The density of the blocks and the block filling degree can be adapted so that the final average density is between 1,900 and 2,000 kg/m^3 after water saturation which corresponds to a dry density of ρ_d= 1,410–1,560 kg/m^3. At this high density the influence of the groundwater composition on hydraulic conductivity and swelling pressure is small.

At the assumed density, the hydraulic conductivity is K ≈ 1.0–3.0·10^{-13} m/s with a swelling pressure of $\sigma_s \approx$ 2,000–7,000 kPa.

From a technical point of view it is probably more demanding to use blocks rather that powder or pellets. However, given the time available until installation it is foreseen that methods for installation and quality control can be developed in due time.

10.6 Engineering principles: Gravel barrier

In Section 10.2 and 10.3 aspects of importance for the long term properties of the hydraulic cage surrounding the outer concrete silo was discussed. Engineering principles for selecting a feasible hydraulic cage medium was presented in Section 9.3.1. Based on these findings it is suggested that a coarse gravel or "macadam" with the grain size of between 16–32 mm is used in the hydraulic cage. This material has a low amount of fine sized material, which provides for a relatively high hydraulic conductivity. The grain size is small enough to yield a uniform pressure on the concrete wall of the outer silo. The material is also very stable and will provide a stable base for the silo construction.

As the layer of gravel beneath the silo will be put in place prior to casting of the concrete structure it will be of great importance to take measures to avoid that no grout accidently enters the gravel bed during casting. It is also important to ensure that the outer silo will remain intact during the entire operational life of the repository in order to avoid that bentonite can enter the gravel bed through cracks in the silo construction.

10.7 Protection of the engineered barriers during the operational phase of the repository

In Figure 10-5 the layout of the Super silo during operation is illustrated.

Many of the processes of importance during the operational period of the repository are dependent on the presence of water or chemical species dissolved in the water. As an example corrosion of the reinforcement bars is governed by the presence of chloride from intruding groundwater.

In order to eliminate or reduce the rate of barrier degradation during the operational period of the repository several methods can be used. The methods of relevance for the Super silo are the same as those described for the Concrete repository (Section 7.5), the Clay repository (bentonite cradle concept, Section 8.4) and the Gravel repository (Section 9.3.2).

10.8 Construction

In the preceding sections issues related to choice of materials for the different components of the engineered barrier systems in the Super silo as well as the processes that may affect the properties of these materials have been discussed. However, in order to ensure that the properties of the engineered barrier systems will be upheld during the entire operational lifetime of the Super silo, the construction methods and sequence for the installation of the materials also need to be carefully considered.

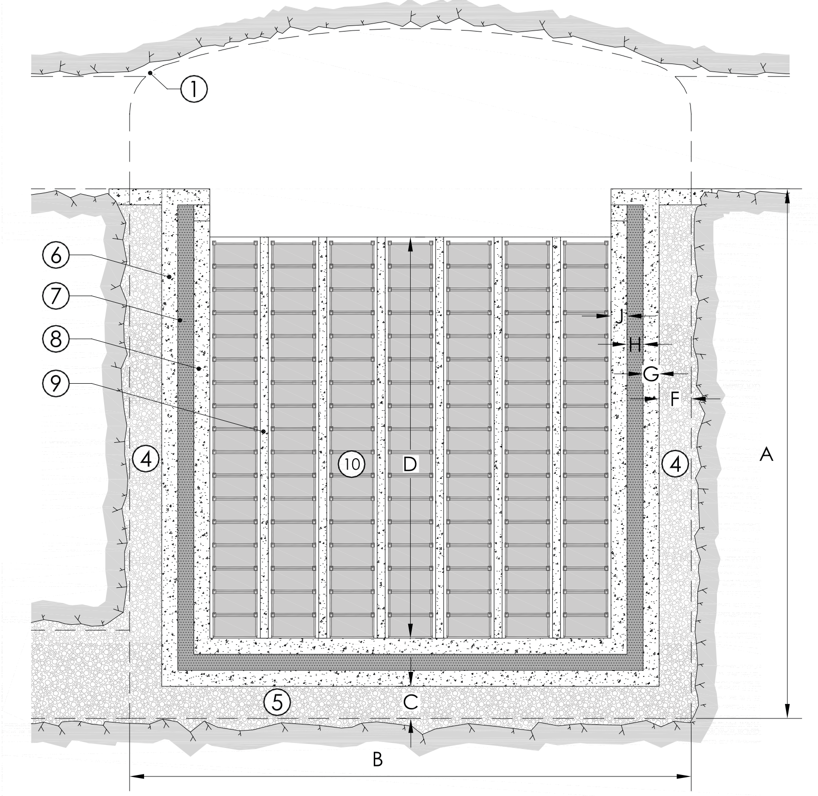


Figure 10-5. The layout of the Super silo during operation. Legend: 1) Theoretical rock cavern contour. 4, 5) Gravel or crushed rock. 6) Reinforced concrete. 7) Bentonite blocks. 8) Concrete. 9) Concrete shaft walls. (0.5 m). 10) Waste container. Approximate dimensions: A = 33 m, B = 35 m, C = 2 m, D = 25 m, F = 2 m, G = 1 m, H = 1 m, J = 1 m.

Based on the information provided in the previous sections, the following reference sequence is suggested for the entire life of the Super silo, including all processes from laying of the foundations to the final sealing of the silo structure:

- Installation of drainage system for the operation period.
- Installation of bottom gravel layer.
- Casting of outer concrete silo.
- Installation of operation period moisture protection for bentonite, if needed.
- Installation of bentonite at the bottom of the silo.
- Casting of inner concrete silo and structures needed to support the waste.
- Installation of bentonite between inner and outer concrete wall.
- Sealing of the bentonite filled slots for the duration of the repository operation period.
- Sealing of the gravel to protect from debris during operation period.
- Installation of waste installation equipment etc.
- Operation period.
- Casting of top supporting structures and upper ceiling of inner silo.
- Removing operational bentonite and gravel sealing.
- Installation of moisture protection for bentonite, if needed.
- Installation of top bentonite layer.
- Installation of moisture protection for bentonite, if needed.
- Casting of outer silo ceiling.
- Installation of top drainage.

Of these processes included in the installation sequence, the four most critical construction stages are discussed in the following sections:

- Casting of the outer concrete silo structure, Section 10.8.1.
- Installation of the bentonite barrier, Section 10.8.2.
- Casting of the inner concrete silo structure, Section 10.8.3.
- Installation of the hydraulic cage, Section 10.8.4.

Furthermore, handling of gas is expected to require additional efforts, see Section 10.8.5.

10.8.1 Casting of the outer concrete silo structure

In principle, there are two different techniques available for the casting of the concrete structures in the Super silo: slip form casting in which the formwork is climbing upwards alongside the newly cast concrete structure, and traditional casting in which an on-site built formwork is utilised. Please refer to Section 7.3.2 for details on the respective methods.

In principle the dimensions of the Super silo makes traditional casting very difficult and instead slip form casting, which was the method of choice for casting of the present silo in SFR, should be used. It is judged difficult, though not impossible, to cast both the inner and the outer concrete structure at the same time. However, as an alternative, casting in two separate stages could also be considered.

10.8.2 Installation of the bentonite barrier

As discussed in Section 10.5 different alternatives exist for the choice of material in the different parts of the volume between the two concrete silos and both pellets and blocks as well as a mixture between bentonite and a non-swelling material can be used. However, independent on choice of type of bentonite or bentonite mixture the most important aspect during the construction and operation of the repository will be to eliminate any interaction between water and the bentonite. In the sections below issues of concern for the installation of the bentonite in the bottom bed and in the walls of the silo are elucidated in more detail. For the bentonite installed during backfill and closure it is assumed that sufficient protection from ground water intrusion in that part of the cavern is provided.

Installation of bentonite in the bottom of the outer silo

Installation of the bentonite or bentonite mixture can be easily done by means of trucks and a short system of conveyor belts delivering the material to the desired site where it is spread out and compacted to the desired thickness and composition by means of suitable equipment. It is here assumed that a door is left in the bottom part of the silo in order to facilitate this process. Owing to the requirements that the bentonite must be protected from interactions with the water a sufficient drainage system as well as a waterproof material needs to be placed between the bentonite and the bedrock in order to prevent that water is sucked into the concrete and further into the bentonite. A drainage system must also be provided on the walls of the rock cavern.

Installation of bentonite in the walls

The installation of bentonite between the silo walls is a more complicated task. If bentonite blocks are installed a rather comprehensive development of the emplacement method and the quality control is foreseen. If instead the material used is an optimised pellet/granule backfill the installation method can probably be made in a simpler and more efficient way. A pellet/granule barrier is not as sensitive to humidity as the blocks. This method will also need development but the feasibility of the installation is deemed much higher than for the block emplacement.

10.8.3 Casting of the inner concrete silo structure

Provided that the inner and the outer concrete structures cannot be casted simultaneously the inner silo will have to be casted in a relatively narrow space and potentially with a layer of bentonite as a foundation. As suggested above, slip form casting is probably the most suitable method for casting of a structure with the dimensions and layout of the inner concrete silo which are more or less identical to those of the silo in SFR which once was casted using the slip form technique.

However, the very limited amount of free space between the outside of the inner silo and the inside of the outer silo will make this process a very challenging task and it is foreseen that great efforts will need to be focused on the development of a method which is suitable for this purpose.

10.8.4 Installation of the hydraulic cage

The installation of the material for the hydraulic cage is not foreseen to cause any practical problems. Care should be taken not to damage the concrete of the outer silo when the hydraulic cage is installed. However, the choice of material in the hydraulic cage implies that this issue will be less critical.

10.8.5 Handling of gas release

In the basic concept the waste is surrounded by bentonite and concrete barriers with only a low gas permeability. If large amounts of gas are produced inside the repository engineered solutions similar to those used in the silo of SFR will need to be applied. In Figure 10-6 the gas ventilation system in the SFR silo is shown.

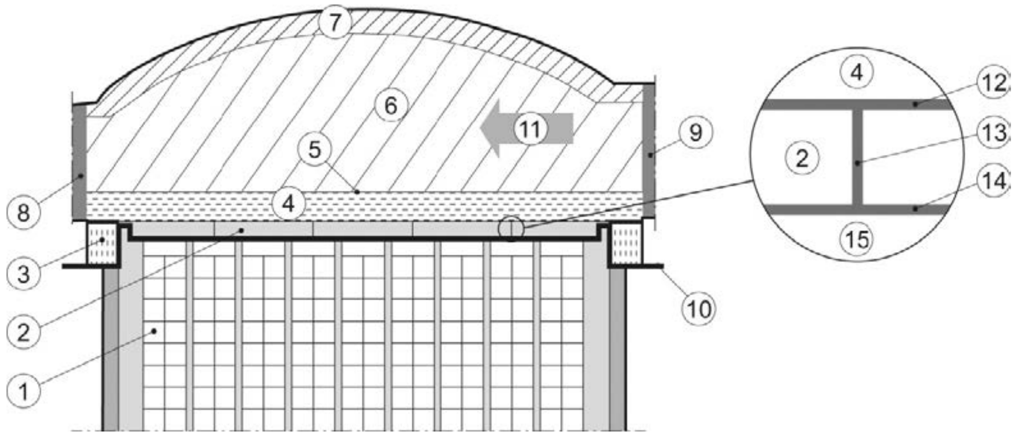


Figure 10-6. Illustration of the structures on top of the silo in SFR with the system for gas release. Legend: 1) Waste. 2) Reinforced concrete with holes for gas release. 3) Bentonite/sand 30/70. 4) Bentonite/sand 10/90. 5) Unreinforced protective concrete. 6) Compacted cohesion less material 7) Cement stabilized sand. 8) Concrete wall. 9) Concrete wall. 10) Boundary between components installed during operation and components installed at closure. 11) Direction of work. 12) Sand, 50 mm. 13) Hole in the concrete to allow for gas release, diameter 100 mm. 14) Sand 50 mm. 15) Permeable cement grout.

10.9 Backfilling of the repository

After the operation period the top of the inner silo, the top bentonite layer and the outer concrete silo lid is installed. After this the upper part of the silo vault is filled with the macadam. Finally a plug is installed in the silo tunnel.

The main concern during this period is to avoid the intrusion of groundwater as this might affect the bentonite. However, it is concluded in Section 10.2.4 that this phase is very short and the influence of the processes during this phase thus are of minor importance.

10.10 Summary and conclusions

In this chapter the basic design of the Super silo was presented in Section 10.1. This was followed by an identification of processes that could affect the engineered barriers during the different phases of the repository, Section 10.2. Finally, in Sections 10.3–10.9 methods to reduce the effects of the identified processes have been discussed and feasible construction methods have been investigated.

It has been shown that the most crucial processes for the Super silo are those that can cause cracking of the outer concrete silo, either by the high external hydrostatic pressure from the groundwater or from the high internal pressure caused by the swelling of the bentonite between the two concrete structures. It was shown that the radius of the outer silo would have to be reduced to 7 metres or less, compared to 16 metres in the basic design. In addition, a bentonite with a low swelling pressure would need to be used in order to reduce these forces.

From a construction point of view it was concluded that the most difficult part of this work would be the casting of the inner concrete silo. The main challenges would be to perform this work in the tight space inside the outer concrete silo as well as handling the fact that the inner silo structure would have to be cast directly on a bed of bentonite or a mixture of bentonite and a non-swelling material.

Finally, the installation of the bentonite between the concrete walls will be demanding, especially if it is decided that bentonite blocks should be used.

11 Operation of the repository

This section gives a brief overview of the foreseen operation phases of the constructed SFL repository. As given by prerequisites in Section 5.3 the operation of the facility will be similar for any of the studied repository concepts.

The operation of the repository will begin with a test operation phase starting around 2045 followed by routine operation with deposition of RWCs, and closure around 2075. After that, the final decommissioning activities, sealing and closure of SFL take part, see Chapter 12.

11.1 Test operation

When the repository has been constructed, the project organisation will hand it over to the operational organisation. During the test operation, the repository is started system by system and the entire repository including handling- and transport equipment is operated with reduced capacity. Waste transport containers are transported and emptied, the first RWCs are deposited and all systems are set in operation, tuned and adjusted for continuous operation.

The rate of deposition is successively increased during the test operation to approach, and finally reach, the capacity for routine operation. In parallel with test operation, a programme for transfer of evaluated experiences is performed as input for continued, routine operation.

11.2 Routine operation

When a permit for routine operation, in accordance with The Nuclear Activities Act (SFS 1984:3), has been granted the routine operation begins. Routine operation is estimated to proceed for approximately 30 years according to current plans for SFL, and comprises the deposition of waste and ordinary maintenance work of the facility and its systems.

11.2.1 Deposition of waste

Descriptions of the deposition process and transport flows must be preliminary established before the repository layout is produced. The following section gives a brief outline of the processes which will act as a basis for the facility design and construction strategies.

The deposition work comprises planning, preparation for deposition, transport of waste containers from the producers to the SFL facility, storage and transport to underground area, unloading, handling and placement of RWCs in the designated disposal area.

Also included in the routine operation are activities like radiation protection work, safe guard, administrative documentation, quality controls and continuous reporting of the performed work.

Waste transport containers, with RWCs inside, are delivered from the waste producer placed on freight stands and with shock absorber mounted. Transport to the SFL facility will be either by land or from ship using a multipurpose vehicle or equivalent. Vehicle and container are controlled at the SFL entry passage regarding physical and nuclear protection, and allowed entry into the secured area after approval. The waste transport container is stored in the terminal building on the surface awaiting transport underground. Shock absorbers are demounted to simplify handling.

When deposition is initiated, the waste transport container, with stand, is loaded onto a transport vehicle inside the surface terminal building. The transport goes via the ramp to the underground disposal area. On a designated handling space in the disposal area, the waste transport container is opened, and the lid lifted off. The RWCs are lifted out and placed on designated deposition position in the deposition compartment with the use of handling and lifting equipment (overhead crane), see Figure 11-1. The principle will be the same for any of the repository concepts described in Chapters 7 to 10.

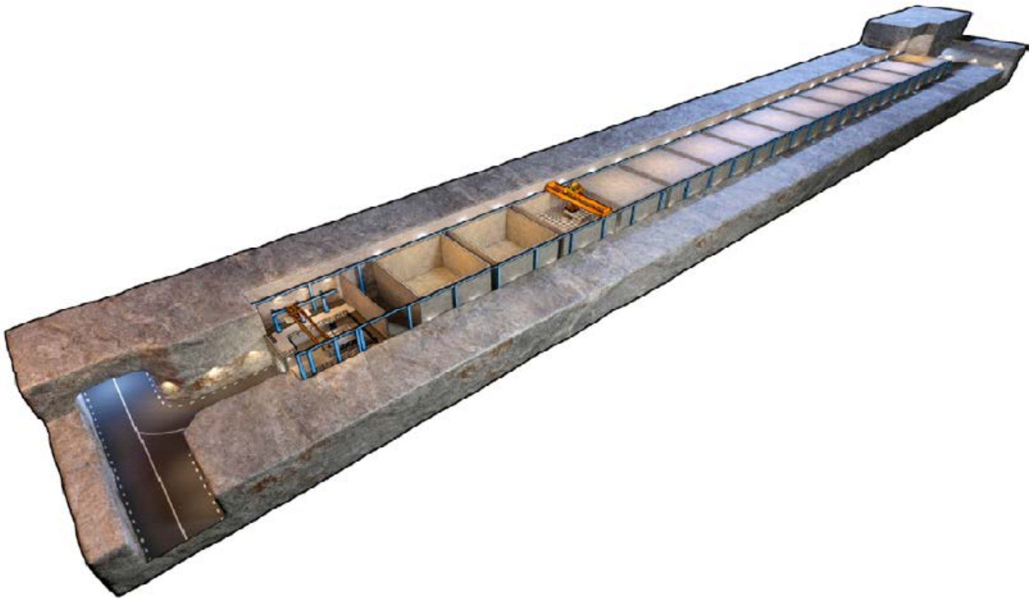


Figure 11-1. Illustration of a rock vault for short-lived intermediate level waste (example from SFR).

When the transport container has been emptied, the lid is lifted back into place and the transport container is closed. Transport vehicle retrieves the transport container back to surface the same way it came and places it for storage in the terminal building. The shock absorbers are mounted and the transport container can later on be transported back to the waste producer for reuse.

11.3 Maintenance

Maintenance is a significant part of the operation comprising repairs or replacement of technical systems, equipment and building parts. Rock work, deposition and backfilling activities with its vehicles and machinery are dependent on service and maintenance.

Maintenance comprises both preventive and corrective maintenance. Resources used will be employed personnel and hired consultants or purchased services. These will be allocated so that the employed personnel are in charge of planning and recurring maintenance for the daily operation. Hired consultants or purchased services will be used for selective measures, as excellence helps and more seldom occurring measures. Premises for maintenance work will generally be placed above ground. Maintenance is to be planned both for the short and long run, and carried out and followed-up using maintenance systems integrated with the system for monitoring daily operations of the repository.

Objects in the repository that will need maintenance are:

- Buildings, ground surfaces and roads.
- Building constructions and installations in the underground part.
- Vehicles and machines.
- Transport devices, lifting equipment and other mechanical equipment.
- Installations for electrical power, process and automation, lighting, ventilation, heat, etc.
- IT and communication systems.
- Physical protection and fire prevention devices.

11.4 Operation management and administration

The operation of the repository will be lead from the surface operations centre. The work comprises planning and managing deposition work, maintenance, backfilling and occasional rock work. From the work management, via the operation central, permits are issued for carrying out all work in the nuclear facility.

The operations centre monitors all on-going activities in the repository as well as sensors and detectors used for surveillance. Monitoring of the physical protection for the nuclear facility is to be separated from other operational monitoring. Communication between these two functions must however be good. Outside of that, directly regarding the daily operation, other activities are also conducted on the surface of the repository such as administration, planning, and quality and safety work.

11.5 Manning

The need for personnel during the routine operation of the repository directs the dimensioning of personnel spaces within the facility.

The estimated need for manning is based on the following assumptions:

- All work underground is carried out during daytime. There are no time critical steps in the handling of the waste that indicate the need for shift work or continuous handling of waste or backfill.
- The operation centre is always staffed during work underground.
- The organization for routine operation of the SFL repository such as administration, planning, quality and safety, monitoring and possibly maintenance etc will be coordinated with SKB's other operations.

The need for personnel in the future SFL-organization for routine operation is anticipated to between 30–50 people. This estimation is dependent on the chosen site for the SFL. Other practical circumstances and changing prerequisites can also make the need for staffing to vary between and during different phases of the SFL lifecycle.

The construction and closure phases of the SFL repository are foreseen to be managed by dedicated organizations on a project basis. Infrastructure needed during the construction of the repository is generally solved with temporary buildings and constructions.

11.6 Vehicles and equipment

The strategy for vehicles and equipment in SFL is to use standard vehicles and standard equipment as far as possible. This is to achieve a high level of availability, maintainability and access to spare parts, as well as to achieve a high level of redundancy in the operation.

The need for equipment and vehicles vary over the different lifecycle phases of the repository. Some of the vehicles and machines are of the type used in mining industry while others are specially developed for particular uses. At this stage of work, the selection of machines and equipment is not complete as work methods are under development.

The internal organization will use vehicles and machines in the daily and continuous long-term operation. The vehicles within the internal organization are mainly concerning the handling of waste transport containers. Vehicles and machines for rock excavation or campaign work, such as backfilling, should not be owned by the internal organization.

All vehicles, equipment and machines require area or space which must be considered in the design of the repository. For instance space for parking and maintenance during construction of the repository.

To determine the precise vehicle and machine needs, function, allocation and operation analyses should be made together with a logistics investigation for the SFL repository when a conceptual design is available.

12 Sealing and closure

In a geological repository the rock mass surrounding the cavern is a part of the barrier system that will prevent the radioactive substances from harming human health or the environment. The tunnels that provide access to the caverns may impair the barrier function of the rock through the creation of open flow paths in the rock and these flow paths must be closed by installing sealing and closure components. The main purposes of the sealing and closure components are:

- Reducing the axial water transport in the tunnels.
- Reducing the water flow from the tunnels to the caverns.
- Supporting the rock and thereby prevent a collapse of the tunnel roof and walls.
- Preventing unauthorised access to the radioactive waste.

In this chapter the components and methods used for sealing and closure of the SFL repository are briefly outlined. At this stage, it is assumed that the design of the components and method for installation will not differ significantly between the different concepts. However, future research and safety analysis will be required before a final design of the sealing and closure components can be presented for each of the individual concepts.

12.1 Definitions

The meaning of the terms backfill, sealing and closure are illustrated in Figure 12-1.

Backfill

The term "backfill" refers to the filling of the caverns in the repository. The backfill design differs between the studied concepts in this report, Chapters 7–10. It is preliminary assumed that a concrete wall will be erected at the interface between the backfill and sealing components to act as support to the backfill in each entrance to the rock cavern.

Sealing

The term "sealing" refers to construction of a section with low hydraulic conductivity at the adjacent tunnels of the caverns. This sealing will minimise the axial flow of groundwater through the cavern access tunnels.

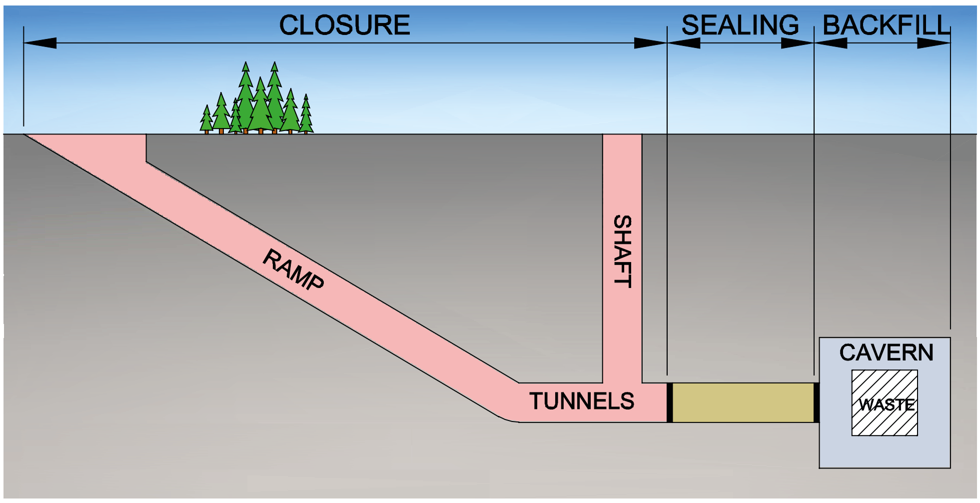


Figure 12-1. *Schematic illustration of the definitions: backfill, sealing and closure.*

Closure

The term "closure" refers to the filling of transport tunnels, shafts and the surface entrance. This action will further reduce the groundwater flow through the caverns and prevent access to the tunnels.

12.2 Sealing

12.2.1 Design

The main component of the sealing is a watertight plug composed mainly of clay such as bentonite. This is in accordance with previous investigations and concepts developed by SKB for the Spent Fuel Repository (Luterkort et al. 2012). In order to ensure a high density and a low hydraulic conductivity of the plug the bentonite must be confined and in the proposed design this is accomplished with concrete plugs.

The tunnel sections where the sealing will be installed must have a limited Excavation Damaged Zone (EDZ) to avoid a shortcut of the sealing of the repository. A limited and discontinuous EDZ can be achieved by using careful drilling and blasting techniques when excavating the tunnels.

12.2.2 Installation

The execution of sealing works will start from a vertical concrete face at the interface to the backfill. The concrete wall will act as an inner formwork when the watertight plug is constructed.

For the low hydraulic conductivity material – here assumed to be bentonite – either compressed blocks or pellets can be used. The method and rate of installation will need to be adapted to the inflow of water at the location of the sealing. Future R&D for the Spent Fuel Repository, and also SFR will give valuable input to both the design and the installation procedure.

12.3 Closure

12.3.1 Design

At this early stage in the process of designing SFL it is assumed that closure of the repository can be designed and installed in the same way as for the Spent Fuel Repository (Luterkort et al. 2012). Please refer to that report for details.

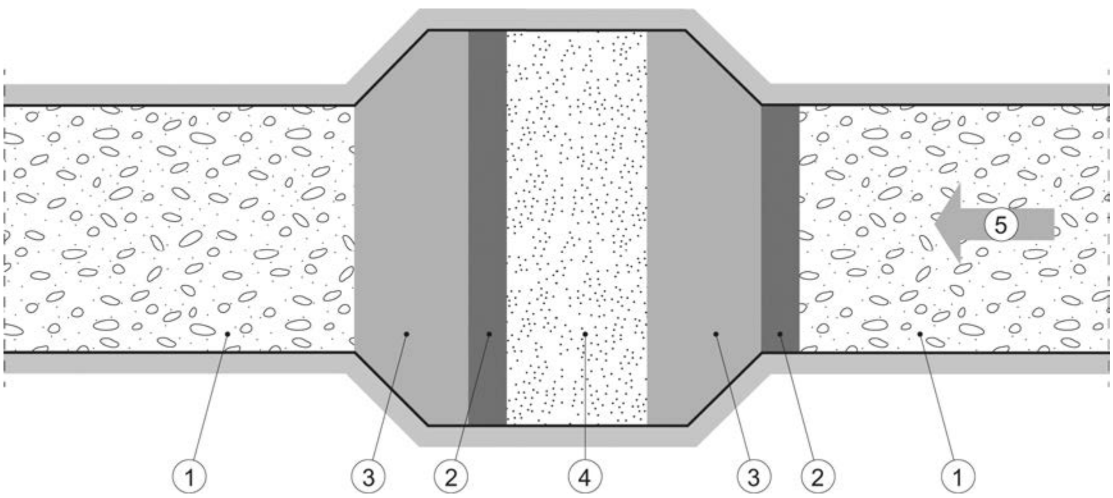


Figure 12-2. Schematic design of a sealing-plug in the repository main tunnel. Legend: 1) Backfill of crushed rock or similar. 2) Retaining concrete walls. 3) Cast concrete. 4) Bentonite. 5) Backfill direction (from the repository cavern and out).

12.3.2 Installation

During the installation of different materials used for closing the repository conventional equipment will be used. Early plans for the SFR suggest that transport by trucks in combination with conveyers is one alternative. Future R&D for the SFR as well as for the Spent Fuel Repository will give valuable input to the installation procedure to be used in SFL.

12.4 Conclusions

The design of the sealing and closure components as well as methods used for installation will mainly depend on the properties of the surrounding rock and is not expected to significantly differ between the studied repository concepts for SFL. For those reasons sealing and closure is not considered to be a determining factor in the selection of a final concept for the SFL repository.

The sealing and closure of the SFL lies many years into the future, which allows for further in-depth studies. Experience will also be gained from operations in SFR and the Spent Fuel Repository.

13 Evaluation of the studied concepts

The main evaluation factors considered in this report relate to the categories "Technology" and "Cost and time", Chapter 4. The evaluation process is described in Chapter 3 and the results are summarised below.

The evaluation is presented in a matrix in which each of the repository concepts are rated using the detailed criteria (or sub-factors) of each of the six evaluation factors. The repository concepts are rated using a three level scale (green, yellow or red) for each of the evaluation sub-factors as outlined in Table 13-1, and written motivations are stated.

The evaluation matrix presented in this chapter has been compiled by the project team (presented in Section 1.4). The rating is the project team's overall assessment, which is based on experience and the technical investigations carried out and presented in Chapters 6–10. Information about operation of the repository (Chapter 11) as well as sealing and closure (Chapter 12) also acts as input to some of the evaluation factors, but these areas are essentially equal for all four concepts.

In the summarizing comparison, the evaluation factors have not been weighted using a weight factor. However, the importance of each sub-factor has been rated to show its priority in the subsequent assessment. The priority level is shown by a traffic light according to the following:

Red light: Essential evaluation sub-factor.

Yellow light: Important evaluation sub-factor.

Green light: Trivial evaluation sub-factor.

Consequently, evaluation sub-factors such as *Technical maturity* (13.2.1) and *Simplicity in design and construction* (13.2.2) are judged as the most important evaluation sub-factors in evaluation category "Technology".

Table 13-1. Values used to rate each concept for a specific evaluation sub-factor. The rating of a repository concept is done by specifying the colour red, yellow or green.

Technical complexity	Risk	Time	Cost
Uncomplicated	Low risk	Fast	Cheap
Challenging	Medium risk	Predictable	Moderate
Complicated	High risk	Time consuming	Expensive

13.1 Personal safety and working environment

13.1.1 Safety at work

Risk of accidents during construction and operation, emergency conditions, possibility to prevent accidents.

Important criterion for comparison between concepts.

Gravel repository	Clay repository	Concrete repository	Super silo
Safe but with one major exception – the inadequate radiation shielding during operation. This may result in the necessity for temporary concrete walls and or thicker walls of the RWCs. Backfilling can form large amounts of dust unless watering of the gravel prior to installation.	Safe. Installation is done with overhead crane. The design requires a concrete structure on pillars where the waste is placed. Heavy work during construction and backfilling phases.	Safe. Installation is done with overhead crane. Heavy work during construction of the concrete structures and in case of backfill with concrete/grout.	High risk of accidents during the complex construction phase, e.g. slip form casting of a tall structure. Also highly complex and heavy installations. Heavy and complicated work during the backfilling phase.

13.1.2 Likelihood and consequence of an accident leading to release of radioactive substances

In the event of an accident, this shall not lead to an unacceptable spread of radionuclides from the RWC.

Trivial criterion for comparison between concepts.

Gravel repository	Clay repository	Concrete repository	Super silo
Lack of sufficient radiation shielding during operation would be even more problematic in case of an accident. Risk for a complicated decontamination process if a leakage occurs into backfill. A large volume of gravel must be controlled and removed as radioactive waste.	The design requires a concrete structure on pillars where the waste is placed. This acts as a radiation shield. The most severe accident is identified as a dropped RWC. If this happens when the RWC is above the concrete structure this can be handled. If the RWC is dropped in the unloading area the consequences can be more difficult to handle.	The concrete structure will provide sufficient protection against radiation. The most severe accident is identified as a dropped RWC. If this happens when the RWC is above the concrete structure this can be handled. If the RWC is dropped in the unloading area the consequences can be more difficult to handle.	The concrete structure will provide sufficient protection against radiation. The most severe accident is identified as a dropped RWC. If this happens when the RWC is above the concrete structure this can be handled. If the RWC is dropped in the unloading area the consequences can be more difficult to handle.

13.1.3 Need for Radiation Protection

Expected dose to staff and visitors during operation and backfilling phases.

Important criterion for comparison between concepts.

Gravel repository	Clay repository	Concrete repository	Super silo
The presented concept holds no radiation protection from the first deposited RWC to completed backfill. Personnel must be isolated from radiation by shielding of the RWCs or by e.g. pre-fabricated concrete beams. If sufficient radiation shielding is arranged the dose to personnel can probably be limited.	The design requires a concrete structure on pillars where the waste is placed. This acts as a radiation shield. Handling of waste by overhead crane. Low doses to personnel are expected.	The concrete structure will provide sufficient protection against radiation. Handling of waste by overhead crane. Low doses to personnel are expected.	The concrete structure will provide sufficient protection against radiation. Handling of waste by overhead crane. Low doses to personnel are expected.

13.1.4 Ability to provide good working environment

General work conditions during the different repository phases; construction, operation and backfilling.

Trivial criterion for comparison between concepts.

Gravel repository	Clay repository	Concrete repository	Super silo
Sufficient radiation protection is assumed to be easily created by erecting temporary concrete structures. Easy layout of the facility with low occupational risks. Dust formation during backfill installation could be avoided by using moist gravel material.	The concrete structure separates RWCs from the staff. No parts of the engineered barrier system will reduce the possibility to provide a good working environment.	The concrete structure separates RWCs from the staff. No parts of the engineered barrier system will reduce the possibility to provide a good working environment.	The concrete structure separates RWCs from the staff. No parts of the engineered barrier system will reduce the possibility to provide a good working environment.

13.2 Feasibility of design and construction

13.2.1 Technical maturity

To what extent is the repository concept developed (known technology, partly known, unknown)?

Essential criterion for comparison between concepts.

Gravel repository	Clay repository	Concrete repository	Super silo
High feasibility of design and construction. Siting of the Gravel repository is expected to be more complicated than for other alternatives since the occurrence of conductive fractures must be very limited.	The feasibility is judged to be good. However, there are a number of technical issues that have to be resolved; the groundwork and the extensive bentonite installation are examples of new design with need for significant development efforts.	Reinforced concrete structures can be manufactured by the use of well known technology and materials. Experiences can be obtained from SFR1 and the expansion project for SFR. Concrete structures without reinforcement is much less well known but has been studied within the SFR expansion project for the 2BMA rock vault. Good understanding of standard concrete. The effect of additives such as fly ash or other mineralogical additives are less well known. This is in particular the case concerning the long-term properties of the material. Good understanding of standard steel reinforcement. Alternative reinforcement such as fibre materials is less well known. Casting of a tall structure without the use of formwork struts will require special precautions and efforts.	What is said for the Concrete repository is also valid for the Super silo. The double-walled silo is a very complex structure. Slip form casting is a well-known technology and experiences can be collected from a large number of different projects. The slip form casting method does not require struts, which is an advantage compared to the Concrete repository. However, a slip form casting puts strong demands on the logistics during the construction work in terms of e.g. material transports. For the installation of bentonite there are several remaining technical issues, e.g. the bearing capacity of bentonite blocks as well as the bentonite installation and quality control. If simplifications of the design are made (e.g. skipping the outer concrete silo, or replacing the betonite block in the bottom of the silo with a compacted mixture of crushed rock) the feasibility can be improved.

13.2.2 Simplicity in design and construction

Difficulty to construct the repository, including rock engineering, manufacturing and installation of engineered barriers, backfill and closure.

Essential criterion for comparison between concepts.

Gravel repository	**Clay repository**	**Concrete repository**	**Super silo**
Simple, by all means. Only major question is if the Gravel repository concept really is feasible with respect to long-term safety (not evaluated in this report).	Rather complicated installation e.g. the backfilling of bentonite needs to be performed continuously once started.	The construction and backfill of the concrete repository should be rather straightforward. Experiences are available from SFR. Difficulties may arise if it is decided that formwork struts cannot be used. To avoid seams, the casting of the concrete structure should be done in one single event. This is of particular importance if it is decided that reinforcement cannot be used as there is then a large potential for the formation of cracks during the hardening of the concrete. The use of concrete or grout as backfill material can be complicated due to the extremely large amounts of material required. This can cause problems with logistics, quality control, and heat generation in the repository with subsequent crack formation. Using gravel as backfill material is probably less complicated.	Even though slip form casting is a well known technology, it will be a very complex task due to the limited space outside the formwork and other complicated logistics at this depth in the rock. Slip form casting will require extensive use of reinforcement in order to provide support during the casting process. Casting a large concrete structure on a bed of bentonite or a sand/bentonite mixture is not a well known technology. Interaction between bentonite and concrete will add extra complexity to the construction work. In general, this is predicted to be a very complicated installation. If simplifications of the design are made (e.g. omitting the outer concrete silo) the feasibility can be improved.

13.2.3 Resistance during the operating period

The resistance of the repository design during the operational period (robustness to meet the intial state as defined by the safety assessment).

Essential criterion for comparison between concepts.

Gravel repository	Clay repository	Concrete repository	Super silo
Good, if the design is made to install backfill gravel just prior to sealing and closure of the facility. This will require the base slab to be placed on pillars. Otherwise, clogging of the gravel medium can become an issue.	Good, if the design is made to install backfill bentonite just prior to sealing and closure of the facility. This will require the base slab to be placed on pillars. An alternative design to the groundwork of pillars would be to construct a cradle in which bentonite blocks are placed prior to the operation period. The concrete base slab is then placed on the bentonite blocks. It is vital that the bentonite below the base slab can be protected from free water and air humidity for the entire operation period. The design of the base slab, "cradle", and the lid has to be made so that this is guaranteed. The mechanical properties of the bentonite block stack below the concrete structure has to be investigated to ensure that it becomes stable enough.	The construction of a concrete structure with a life time of about 100 year in a marine environment can be done according to well known standards and by the use of well known technology. It requires that drainage systems and tunnel cloths are installed and well functioning during the entire operational time. The optimal climate in the repository must be considered when the ventilation etc is designed. Some carbonation can be expected. This is taken into consideration when the concrete structures are designed. During design of the repository all load cases must be taken into consideration, including such risk as falling of waste container etc. It is not expected that the materials used in the engineered barriers will adversely affect the waste containers during the open period of the repository.	What is said for the concrete repository is also valid for the Super silo. Chemical and mechanical interactions between the concrete structures and the bentonite must be taken into consideration during the design of the repository, in the development of concrete recipe and when dimensioning the bentonite. Swelling of the bentonite must be avoided until the hydrostatic pressure on the outer silo is fully developed (several years after closure). This will require late installation of bentonite or drainage and other types of protection, such as a tunnel cloth, during the operation period. The bentonite in the bottom of the silo must be installed before start of operations. There are risks that bentonite blocks deteriorate during the operation period leading to settlement of inner silo. The design can be improved, e.g. by replacing the bentonite blocks with a mixture of crushed rock and bentonite.

13.2.4 Feasibility of quality control and maintenance (of construction)

Is it possible to correct deficiencies in safety or impact on the initial conditions?

Essential criterion for comparison between concepts.

Gravel repository	Clay repository	Concrete repository	Super silo
High feasibility of quality control and maintenance.	The quality control of the bentonite is very important for the function of the concept. Robust and quick systems for quality control need to be developed. The large amounts of bentonite used for the backfill should give a reasonable margin to the requirements. Easy maintenance during operation.	The operational structures can be controlled during the operational period of the repository (this does not include the floor and the walls inside the waste compartments). The quality control of concrete backfilling will need a lot of planning. Maintenance during the operation period is feasible.	Difficult to control the status of the engineered barrier system once deposition of the waste has started. Difficult to correct deficiencies in the grouting. Maintenance during the operation period can be complicated.

13.2.5 Feasibility of physical protection and safe guard

Possibilities of the repository design to achieve good prerequisites for physical protection and safe guard issues.

Trivial criterion for comparison between concepts.

Gravel repository	Clay repository	Concrete repository	Super silo
Can be managed.	Can be managed.	Can be managed.	Can be managed.

13.3 Feasibility of technology and method of operation

13.3.1 Easiness in method

Conditioning, handling, deposition and grouting of the waste packages. What are the problems and risks with the chosen method of operation?

Important criterion for comparison between concepts.

Gravel repository	Clay repository	Concrete repository	Super silo
Conditioning of the waste is ecpected to be done in a separate facility and is independent of the concept. The waste containers will be deposited by the use of overhead crane or similar, which is a well known method. The waste containers are not expected to adversely affect the engineered barrier during operation of the repository. Easy handling and easy access to the RWCs during operation (provided that sufficient radiation protection is arranged).	Conditioning of the waste is ecpected to be done in a separate facility and is independent of the concept. The waste containers will be deposited by the use of overhead crane or similar, which is a well known method. The waste containers are not expected to adversely affect the engineered barrier during operation of the repository. Easy handling and easy access to the RWCs during operation.	Conditioning of the waste is ecpected to be done in a separate facility and is independent of the concept. The waste containers will be deposited by the use of overhead crane or similar, which is a well known method. The waste containers are not expected to adversely affect the engineered barrier during operation of the repository. If grouting between RWCs is to be done already during the operational period it is vital to find a grout recipe that is robust over several decades.	Conditioning of the waste is ecpected to be done in a separate facility and is independent of the concept. The waste containers will be deposited by the use of overhead crane or similar, which is a well known method. The waste containers are not expected to adversely affect the engineered barrier during operation of the repository. Grouting between RWCs is done during the operational period thus it is vital to find a grout recipe that is robust over several decades. The majority of the barrier material is installed during the construction or operation phase and only the backfill material on the top of the engineered barrier system is installed during the closure of the repository. This makes logistics less complex than is the case for the concrete repository.

13.3.2 Maturity in technology

Maturity in technology with respect to operational tasks in the repository.

Trivial criterion for comparison between concepts.

Gravel repository	Clay repository	Concrete repository	Super silo
Methods used during operation will be similar to SFR and thus well known.	Methods used during operation will be similar to SFR and thus well known.	Methods used during operation will be similar to SFR and thus well known.	Methods used during operation will be similar to SFR and thus well known.

13.3.3 Safety during operation

Reliability, possibility to correct in case of accident, robustness for unforeseen events.

Important criterion for comparison between concepts.

Gravel repository	Clay repository	Concrete repository	Super silo
Easy to check that the waste containers are properly deposited in the repository. It is possible to correct an erroneous deposition of a RWC and also to retrieve a RWC from the repository, if required. Difficult to repair machinery and conduct maintenance due to lack of radiation shielding in the original repository design. If sufficient radiation protection is arranged the repository environment will be acceptable and safe from workers point of view.	Easy to check that the waste containers are properly deposited in the repository. It is possible to correct an erroneous deposition of a RWC and also to retrieve a RWC from the repository, if required.	Easy to check that the waste containers are properly deposited in the repository. It is possible to correct an erroneous deposition of a RWC and also to retrieve a RWC from the repository, if required.	Easy to check that the waste containers are properly deposited in the repository by using e.g. a camera that is lowered into the silo. Correctional means are more difficult. There is a risk that an entire shaft has to be sealed and closed in the case of a mishap during the deposition of a RWC. The continuous grouting of the waste containers during operation makes retrieval of a RWC for correctional measures impossible (or at least very complex).

13.3.4 The possibility for quality control of deposited waste etc

The possibility of quality control (of deposition, conditioning etc). Is it possible to correct deficiencies in safety or impact on the initial state?

Important criterion for comparison between concepts.

Gravel repository	Clay repository	Concrete repository	Super silo
Quality control of the conditioning of the waste is done in a separate facility and does not differ between the concepts. Easy to control that the waste containers are being deposited in the pre-defined position. Possible to correct and retrieve RWCs.	Quality control of the conditioning of the waste is done in a separate facility and does not differ between the concepts. Easy to control that the waste containers are being deposited in the pre-defined position. Possible to correct and retrieve RWCs.	Quality control of the conditioning of the waste is done in a separate facility and does not differ between the concepts. Easy to control that the waste containers are being deposited in the pre-defined position. Possible to correct and retrieve RWCs.	Quality control of the conditioning of the waste is done in a separate facility and does not differ between the concepts. Easy to control that the waste containers are being deposited in the pre-defined position. More difficult to correct and retrieve RWCs. There is a risk that an entire shaft has to be sealed and closed in the case of a mishap during the deposition of a RWC.

13.4 Flexibility

13.4.1 Flexibility in technology and method of operation

Adapting to changing volumes, waste types, packaging, access to different modes of transport, adaptation to wastes that are physically, chemically or radiologically difficult to handle.

Important criterion for comparison between concepts.

Gravel repository	Clay repository	Concrete repository	Super silo
The repository concept can handle waste containers with different dimensions, both known and unexpected. Requires a new lifting device though. Flat base slab and no additional barriers provides for possible use of different equipment during placement of RWCs. Easy adaptation to different types of waste and changing volumes, however specially designed containers can be necessary. Radiation protection during operation must be constructed for the specific purpose.	The repository concept can handle waste containers with different dimensions, both known and unexpected. Requires a new lifting device though. Difficult to expand once taken into operation unless this is not taken into consideration during design and choice of site. One rock vault can be expanded but this is not recommended once it has been taken into operation. Waste that is difficult to handle can be placed in specially designed waste containers with standard dimensions and can thus be handled. Radiation shielding during operation is sufficient.	The repository concept can handle waste containers with different dimensions, both known and unexpected. Requires a new lifting device though. Difficult to expand once taken into operation unless this is taken into consideration during design and choice of site. One rock vault can be expanded but this is not recommended once it has been taken into operation. Waste that is difficult to handle can be placed in specially designed waste containers with standard dimensions and can thus be handled. Radiation shielding during operation is sufficient.	Can handle waste containers with different dimensions both known and unexpected as long as they are smaller than the standard waste container so that they fit into a standard container. Larger waste containers cannot be handled in this repository. Not possible to expand at any stage. If a larger repository volume is required another silo has to be constructed in a separate part of the repository. Waste that is difficult to handle can be placed in specially designed waste containers with standard dimensions and can thus be handled. Radiation shielding during operation is sufficient.

13.4.2 Flexibility in design and construction

Flexibility in layout, the ability to build in stages, adjusting the design to changing volumes, waste types, packaging, adaptation to different geological environments.

Essential criterion for comparison between concepts.

Gravel repository	Clay repository	Concrete repository	Super silo
The repository can be expanded if this is planned for during the design and choice of site. The proposed design is very flexible with a base slab on a load bearing bed of cage medium is relatively independent of RWC's size and weight. The cage medium and the proposed installation with conveyers are likely to handle a wide spectrum of RWC designs. The Gravel repository will benefit from a surrounding low-permeable rock. The cage medium itself will not be negatively affected by a relatively high permeable rock. The Gravel repository can be constructed as either one large or several smaller caverns of desired shape and dimensions to suite the selected site.	The repository can be expanded if this is planned for during the design and choice of site. The repository could be constructed in two or more steps if this is planned for. However, due to the small volume of waste this is not recommended. Waste that is difficult to handle can be placed in specially designed waste containers with standard dimensions and can thus be handled. This does not have to be considered during the design and construction phases. Can be located at any site where the rock is of sufficiently good quality for the excavation of a rock vault with the required dimensions. The length of the repository increases the risk that the repository will intersect one or several fault zones or cracks. The Clay repository can be constructed as either one large or several smaller caverns of desired shape and dimensions to suite the selected site.	The repository can be expanded if this is planned for during the design and choice of site. The repository could be constructed in two or more steps if this is planned for. However, due to the small volume of waste this is not recommended. Waste that is difficult to handle can be placed in specially designed waste containers with standard dimensions and can thus be handled. This does not have to be considered during the design and construction phases. Can be located at any site where the rock is of sufficiently good quality for the excavation of a rock vault with the required dimensions. The length of the repository increases the risk that the repository will intersect one or several fault zones or cracks. The high hydrostatic pressure at the planned repository depth will require that the grout inside the barrier provide enough support so that the barriers do not collapse under this pressure. The Concrete repository can be constructed as either one large or several smaller caverns of desired shape and dimensions to suite the selected site.	The repository can be expanded with a new silo if this is planned for during the design and choice of site. The repository could be constructed in two or more steps if this is planned for. However, due to the small volume of waste this is not recommended. Waste that is difficult to handle can be placed in specially designed waste containers with standard dimensions and can thus be handled. This does not have to be considered during the design and construction phases. Can be located at any site where the rock is of sufficiently good quality for the excavation of a rock vault with the required dimensions. The fact that the repository is more compact than the long rock vaults increases the chances of finding a suitable site. The high hydrostatic pressure as well as the high rock tensions at the planned repository depth can make it impossible to construct a Super silo. This could be handled if several small silos are built instead.

13.5 Cost

13.5.1 Investment

Infrastructure, facilities (above and below ground), rock excavation, materials, machinery and equipment, technical systems.

Essential criterion for comparison between concepts.

Gravel repository	Clay repository	Concrete repository	Super silo
Investment cost for site investigations, infrastructure, ramp and shafts, facilities above and below ground is about the same for all repository concepts. Specific cost for the Gravel repository is about **200 MSEK**. *Explanation*: Rock excavation of 80,000 m^3: 90 MSEK. Re-use of materials: 15 MSEK. Simple concrete base slab: 20 MSEK. Technical systems 50 MSEK. Misc. 15%.	Investment cost for site investigations, infrastructure, ramp and shafts, facilities above and below ground is about the same for all repository concepts. Specific cost for the Clay repository is about **470 MSEK**. *Explanation*: Rock excavation of 80,000 m^3: 90 MSEK. Bentonite backfill material: 200 MSEK. Concrete structure: 50 MSEK. Technical systems 50 MSEK. Misc. 20%. N.B. In addition there is a need for a production facility for bentonite blocks and pellets. Same facility as for the Spent Fuel Repository?	Investment cost for site investigations, infrastructure, ramp and shafts, facilities above and below ground is about the same for all repository concepts. Specific cost for the Concrete repository is about **395 MSEK**. *Explanation*: Rock excavation of 80,000 m^3: 90 MSEK. Construction of concrete barriers: 65 MSEK. Concrete backfill: 110 MSEK. Technical systems 50 MSEK. Misc. 25%.	Investment cost for site investigations, infrastructure, ramp and shafts, facilities above and below ground is about the same for all repository concepts. Specific cost for the Super silo is about **610 MSEK**. *Explanation*: Rock excavation 75 MSEK. Material cost and construction of concrete barriers 200 MSEK. Material cost and installation of bentonite barriers 100 MSEK. Technical systems 75 MSEK. Misc. 30–40% N.B. In addition there is a need for a production facility for bentonite blocks. Same facility as for the Spent Fuel Repository? N.B. Figures above are based on one large silo. As discussed in Chapter 10, the outer concrete wall of the silo construction will not resist the hydrostatic load at the planned repository depth during the resaturation phase. Instead several small silos will have to be constructed (unless the design is changed). This will increase the investment cost further.

13.5.2 Operation and maintenance

Costs for staff, energy, maintenance, supplies, availability, safety and security, decommissioning and closure.		*Important criterion for comparison between concepts.*

Gravel repository	Clay repository	Concrete repository	Super silo
Ordinary maintenance and operation costs. Uncomplicated closure of the facility. All supporting systems such as electricity, ventilation etc are independent of choice of concept. The main requirements on these systems originate in the requirements for a good working environment. Backfill of the repository rock vault can be done by the use of conveyor belts. This is a known technology.	Ordinary maintenance and operation costs. Uncomplicated closure of the facility. All supporting systems such as electricity, ventilation etc are independent of choice of concept. The main requirements on these systems originate in the requirements for a good working environment. Backfill of the repository rock vault might require mainly automated processes for bentonite emplacement. Such technology is already under development by SKB.	Ordinary maintenance and operation costs. Uncomplicated closure of the facility. All supporting systems such as electricity, ventilation etc are independent of choice of concept. The main requirements on these systems originate in the requirements for a good working environment. Backfill of the repository rock vault with concrete mixtures might require extensive personnel resources due to the complex logistics and large amounts of material that has to be handled.	Ordinary maintenance and operation costs. Uncomplicated closure of the facility. All supporting systems such as electricity, ventilation etc are independent of choice of concept. The main requirements on these systems originate in the requirements for a good working environment. Backfill of the repository rock vault will probably require less personel, since the backfill volume is smaller compared to the other concepts.

13.5.3 Research and development

Costs for research and development needed for realization of the repository concept (with focus on the technical challenges).		*Important criterion for comparison between concepts.*

Gravel repository	Clay repository	Concrete repository	Super silo
The basic concept will require limited R&D efforts. However, the Gravel repository concept will most probably put strict requirements on the long-term stability and integrity of the RWCs. This will likely demand significant R&D efforts.	The installation of bentonite as backfill material in a rock cavern has been studied in the SFR extension project. It will require moderate development. The handling of water will require some development even though SKB will achieve knowledge from the backfilling of deposition tunnels in the Spent Fuel Repository.	Basically known technology. If standard concrete and other materials are used, only limited R&D efforts are foreseen. If non-standard materials and methods are used, the cost is dependent on the ambitions and which materials and methods that are studied.	Significant research needed to develop feasible methods for construction and control of initial state. The construction of a Super silo is judged to be a complicated task compared to any of the other repositories, and also compared to other comparable concrete structures in society. For that reason large scale experiments will probably be needed, resulting in high costs for demonstrations. If non-standard materials and methods are used the cost is dependent on the ambitions and which materials and methods that are studied. In this case the cost will be much higher compared to other concepts.

13.6 Time

13.6.1 Schedule for realization of the repository concept

Likelihood that the program can be implemented in accordance with the time schedule.

Essential criterion for comparison between concepts.

Gravel repository	Clay repository	Concrete repository	Super silo
Installation of the backfill material (the main barrier) is far in the future. Long-term studies of the cage medium's hydraulic conductivity behaviour are necessary. If that issue is solved the time assigned should be adequate. It is likely that long-term safety studies of a Gravel repository will require development of sealed containers. That topic can affect the schedule for implementation in a significant way.	Installation of the backfill material (the main barrier) is far in future. A clay repository is a well known business for SKB.	Concrete structures are basically known technology. Installation of the concrete backfill material is far in future. A concrete repository is a well known business for SKB.	Interfaces between the engineered barriers in the Super silo will need development and demonstrations. Installation of backfill material is far in future.

14 Summary and conclusions

In this report, four different concepts for the future SFL have been described and a basic design for each of these concepts has been presented. Based on the design and the proposed materials for the respective concept, processes which may affect the engineered barrier systems have been identified. This has then for each concept been followed by a discussion concerning detailed selections of barrier materials and the feasible methods to use for construction and installation of the engineered barrier systems.

With that as a background an evaluation based on the evaluation categories *Technology* and *Cost and time* was presented in Chapter 13. In this chapter an overall summary of the performed evaluation is first presented followed by the conclusions that have been made from this study.

14.1 Summary of the comparison between concepts

The tables below show the summarised result of the evaluation matrix in Chapter 13, with short comments on the assessment.

14.1.1 The Gravel repository

1	Lack of radiation shielding in the original design, must be arranged.
6	Siting is complex. Difficult to decontaminate if an accident occurs. Questions raised on long-term behaviour of the hydraulic medium.
12	Simple design, easy construction, operation and control. Flexible. Cheap.

14.1.2 The Clay repository

0	No sub-criterion was rated as critical.
6	Concrete structures as well as the bentonite emplacement and control procedures need development. Needs grouting of RWCs. Costly.
13	Safe design, feasible for operation and control. Flexible.

14.1.3 The Concrete repository

0	No sub-criterion was rated as critical.
6	Heavy construction work. Backfilling with concrete materials needs further development. Grouting between RWCs is important. Costly.
13	Known technique from SFR, safe design, feasible for operation and control. Flexible.

14.1.4 The Super silo

7	Complex design, construction and installation. Limited waste volume per silo. Barrier interface issues. Big development needs. Expensive.
6	Construction hazards and operational risks, difficult grouting between RWCs and complicated control of the initial state. Inflexible design.
6	Safe design, feasible for operation and control.

14.2 Conclusions

This section describes in summary the review of each concept with respect to the evaluation categories *Technology* and *Cost and time*.

14.2.1 Technology aspects

The Concrete repository can be constructed with known and established technology. It can be built either as one large or several smaller rock caverns with the desired shape and dimensions, which gives flexibility to adapt the design to local geological conditions. The main advantages of this concept are that it will provide an alkaline environment which will provide for a very low corrosion rate of the metallic waste and also provide strong sorption of the radionuclides on the cement minerals. Further, the proposed grout filled waste containers will provide a mechanically stable waste matrix which together with the grout between the containers will provide a strong support for the concrete structure during the resaturation of the repository after closure. Furthermore, the proposed concrete structure will provide radiation shielding during operation.

The major concern related to the technical feasibility of the concept is the possible formation of cracks in the concrete structures and in the concrete backfill. Cracks can be formed during construction, operations and backfill, and effort has to be focused on developing the design and construction in order to control the formation of cracks.

The Gravel repository is considered to be the easiest concept to design and build and the concept contains no major challenges and very low risks from a technical standpoint. The repository is also cheap and flexible.

The basic design lacks radiation protection during the operational period, which is a severe drawback. This can be solved relatively easily though, by erecting a temporary concrete structure around the waste. At present, there are questionmarks regarding the possible clogging over time of the gravel medium as well as for other long-term safety aspects of a hydraulic cage.

The Clay repository can be constructed either as one large or several smaller rock caverns with the desired shape and dimensions which gives flexibility to adapt the design to local geological conditions. A major advantage of this concept is that it utilises a natural material with well-known properties. The clay will, owing to its very low hydraulic conductivity, ensure a limited release rate for radionuclides for very long times. Furthermore, the proposed grout filled waste containers will provide a mechanically stable waste matrix which is a prerequisite for any repository concept with swelling clay, while the proposed temporary concrete structure will provide radiation shielding during operation.

In the basic design, there is no bentonite installed in the rock cavern prior to backfill. The challenges for the bentonite installation comprise achieving a high enough density and a fast installation. The high density is required to achieve low hydraulic conductivity, high swelling pressure and a high resistance to the degrading processes in the repository. High installation rate is necessary to avoid practical problems mainly related to the effects of water inflow during installation. If a design alternative where the clay is installed already during the construction of the repository is chosen, there will be additional needs for protection of the clay during the operational phase, to prevent early swelling as well as piping and erosion of the clay.

The Super silo is a very complex design that requires extensive technical development in order to be designed and constructed. The main advantage of this concept is that it provides a combination of several engineered barriers which together will limit the release rate of radionuclides. In addition the radiation shielding during operation is very good.

A number of concerns have been raised among which the most important relates to the construction of the Super silo. In the basic design it is suggested that the diameter of the outer concrete silo should be about 35 metres. However, calculations show that the forces acting on the silo during the different repository phases restrict the diameter to a maximum of about 14 metres. As a result, the available disposal volume in the silo is dramatically reduced and a number of silos would therefore be needed to reach a satisfactory storage volume. Bentonite clay with low swelling pressure can probably be used between the concrete cylinders to reduce loads on the outer concrete cylinder from the swelling clay, but this would not solve the problem with the high hydrostatic pressure from the groundwater during the resaturation of the repository. Finally, the uncertainties and risks related to the technical development of a Super silo are considered to be larger than for any of the other studied concepts.

In conclusion, from a technology viewpoint the Concrete repository and the Clay repository are the two most feasible concepts for future development.

14.2.2 Cost and time aspects

In the evaluation of cost and time aspects in Sections 13.5 and 13.6, it was concluded that the Gravel repository is the least expensive concept whereas the Super silo is the most expensive, with the Concrete and Clay repositories between them.

However, the costs for the repository also include costs for access tunnels and surface facilities. As these costs are estimated to be much higher than the costs for the disposal vaults, the assumed differences in cost for the different concepts will be small in comparison with the total cost for the repository. The single most important factor affecting time and cost aspects will therefore be the possibility of co-locating the SFL repository with any other of SKB's repositories. With the use of the same surface facilities and a common ramp (complete or partly) down to the disposal depth for SFL, the costs for SFL would be markedly reduced as well as the time for construction of the repository.

15 Future work

In the following sections identified areas related to technological aspects that require focused efforts are presented for the Concrete repository and the Clay repository. In addition, there are common development areas such as technical systems and waste containers for the LL-LILW.

An important basis for the first development phase will be a long-term safety statement within the next couple of years. Conclusions from these overall safety studies will be valuable input to the design work for a Clay repository or a Concrete repository as well as for the waste containment. Research areas of importance for the long term safety are handled in the RD&D Programme 2013 (SKB 2013).

15.1 The Concrete repository

As concluded in Section 14.2.1 the main concern for the Concrete repository is how to control the formation of cracks in the concrete structure and in the backfill material. The following focus areas have been identified:

- Design and construction of the concrete structure.
- Backfilling of the repository with concrete and/or grout.
- Interactions between the bedrock and the backfill material.
- The impact of concrete additives on the long term safety of the repository.
- Handling of gas generated by processes inside the repository.
- Corrosion of reinforcement bars, waste and waste containers.
- Transport logistics.

Development work is required to be able to construct the Concrete repository with as small uncertainties regarding its initial state as possible. For example, it is of interest to be able to make realistic rather than conservative estimates of the amount of cracks derived from shrinkage etc in the backfilled concrete volume. The interface between rock and concrete is a recognized challenge. Will a shrinkage gap arise and should it then be filled with something? How will possible movements in the rock affect the concrete barrier? Furthermore, the evolution of gas in the repository and the transportation of gas through the concrete barrier are important areas to investigate, including developing techniques to limit the possible adverse affects of gas transport through the barrier. A recommended approach is to describe different methods for casting and installation of barriers, including grout, to reach the expected initial state.

Possible additives in the concrete should be investigated with respect to their impact on the concrete mechanical and chemical stability and the mobility of radionuclides. The logistics of transporting large amounts of concrete for backfill also needs to be highlighted.

R & D efforts to design and construct the Concrete repository are expected to be relatively limited since proven technology can be used. The description of the concrete barrier provides the conditions for the safety assessment to achieve an understanding of the processes in the repository. This in turn creates the conditions for the progress in research and development, as weak points can be identified.

15.2 The Clay repository

As concluded in Section 14.2.1 the main concern for the Clay repository is related to how to protect the bentonite during the construction and operational phases. The following focus areas have been identified:

- Composition of the bentonite and the density at the initial state.
- Choice of method for fabrication of the bentonite
- Development of an installation sequence for the bentonite.
- Development of a backfill emplacement method with adequate equipment.

Requirements on the quality of the bentonite will be addressed in coming assessment of the long-term safety. It is recommended to start the development in a desk study to present different Clay repository designs and related installation methods. The outcome is for instance a description of what density can be achieved for the different options.

The installation sequence for backfill with bentonite clay needs to be developed. The main idea of the proposed solution is that the waste is enclosed on all sides by bentonite. Particularly the intended installation procedure needs to be configured with respect to the structures that are required during operation of the repository.

15.3 Waste containers

In this study it has been assumed that the waste will be delivered to the repository in standardised containers independent on type of waste but the waste containers themselves have not been further discussed. This is done in a separate study (Pettersson 2013), which suggests that waste containers for the LL-LILW can be developed into a standardized set of containers for rational handling and transportation of the RWCs to SFL. These containers are shown in Section 5.2. As an alternative, an improved container which can be credited with a long-term safety function is also discussed by Petterson (2013).

15.4 Technical systems

Development and design of processes, technical systems and equipment will be carried out according to well established routines. The activities in the design development must be performed methodically in order to ensure that:

- Technical systems and support systems fulfil requirements and demands from laws, authorities and internal requirements.
- Correct activities are planned for the development or enhancement of technical systems.
- Requirements, achievements and targets are verified and validated against stakeholders and authorities.

Design of technical systems must also be carried out with respect to human possibilities and limitations. In interaction between man, technique and organisation deficiencies that can occur are to be detected, taken in to consideration and handled in the design work. This is an important part in developing new processes and techniques and thereby creating the right conditions for safe and reliable operation.

This work will be initiated in the coming years, resulting in an overall mapping of processes needed for the SFL system. Activities will be done in coordination with the design development described in Section 15.1, 15.2 and 15.3. See also RD&D Programme 2013 (SKB 2013).

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