Technical Report

TR-06-21

Initial state report for the safety assessment SR-Can

Svensk Kärnbränslehantering AB

October 2006

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

Initial state report for the safety assessment SR-Can

Svensk Kärnbränslehantering AB

October 2006

Preface

This document compiles information on the initial state of the fuel and the engineered parts of a KBS-3 repository. It supports the safety assessment SR-Can, which is a preparatory step for a safety assessment that will support the licence application for a final repository in Sweden.

The work of compiling this report has been lead by Karin Pers, Kemakta Konsult AB. She has also been the main editor of the report.

The following persons have had the main responsibilities for specific subject areas: Patrik Sellin, SKB (fuel, buffer and backfill), Ola Karnland, Clay Technology (buffer and backfill), Lennart Börgesson, Clay Technology (buffer and backfill), Harald Hökmark, Clay Technology (buffer and backfill), David Gunnarsson, SKB (buffer and backfill), Lars Werme, SKB (canister), Eva Widing, SKB (repository layout, structural and stray materials), Ann Emmelin (low pH materials), Gunnar Ramqvist, SKB (borehole seals).

Stockholm, October 2006

Allan Hedin
Project leader SR-Can

Summary

A comprehensive description of the initial state of the engineered parts of the repository system is one of the main bases for the safety assessment. There is no obvious definition of the time of the initial state. For the engineered part of ther repsotiory system, the time of deposition is a natural starting point and the initial state in SR-Can is, therefore, defined as the state at the time of deposition for the engineered barrier system.

The initial state of the engineered parts of the repository system is largely obtained from the design specifications of the repository, including allowed tolerances or allowance for deviations. Also the manufacturing, excavation and control methods have to be described in order to adequately discuss and handle hypothetical initial states outside the allowed limits in the design specifications. It should also be noted that many parts of the repository system are as yet not finally designed – there can be many changes in the future. The design and technical solutions presented here are representative of the current stage of development.

Overview of the engineered part of the repository system

The repository system is based on the KBS-3 method, in which copper canisters with a cast iron insert containing spent nuclear fuel are surrounded by bentonite clay and deposited at 400–700 m depth in saturated granitic rock.

The facility design comprises rock caverns, tunnels, deposition positions etc. Deposition tunnels are linked by tunnels for transport and communication and shafts for ventilation. One ramp and five shafts connect the surface facility to the underground repository. The ramp is used for heavy and bulky transports and the shafts are for utility systems and for transport of excavated rock, backfill and staff.

For the purposes of the safety assessment, the engineered parts of the repository system have been sub-divided into a number of components or sub-systems. These are:

- The fuel, (also including cavities in the canister since strong interactions between the two occur if the canister is ruptured).
- The cast iron insert and the copper canister.
- The buffer in the deposition hole.
- The bottom plate in the deposition hole.
- The deposition tunnel with its backfill material.
- Other repository cavities with their backfill materials, e.g. transport tunnels, shafts and central underground area.
- Repository plugs.
- Investigation boreholes with their sealing material.

This particular sub-division is dictated by the desire to define components that are as homogeneous as possible without introducing an unmanageable multitude of components. Homogeneity facilitates both characterisation of a component and the structuring and handling of processes relevant to its long-term evolution. Also, the importance of a particular feature for safety has influenced the resolution into components. In principle, components close to the source term and those that play an important role for safety are treated in more detail than peripheral components. The initial state of each component in the engineered parts of the repository system is described by a specified set of physical variables, selected to allow an adequate description of the long-term evolution of the component in question in the safety assessment.

Fuel/cavity in canister

The total quantity of fuel obtained from the Swedish nuclear reactors will depend on operating time, energy output and fuel burn-up. At the end of 2005, approximately 6,300 tonnes of spent fuel had been generated. With an operating lifetime of 40 years for all reactors, except for Barsebäck 1 and 2 which were taken out of operation during 1999 and 2005, respectively, the total quantity of spent fuel has been estimated as 9,300 tonnes.

Several types of fuel are to be deposited in the repository. For the option with 40 years of reactor operation, the quantity of BWR fuel is estimated at 7,000 tonnes and the quantity of PWR fuel at 2,300 tonnes. In addition, 23 tonnes of mixed-oxide fuel (MOX) and 20 tonnes of fuel from the reactor in Ågesta will be deposited. The Ågesta fuel is heavy water reactor fuel.

Nuclear fuel consists of cylindrical pellets of uranium dioxide. The pellets are stacked in approximately 4-metre-long cladding tubes of Zircaloy, a durable zirconium alloy. The tubes are bundled together into fuel assemblies. Geometric aspects of the fuel cladding tubes of importance in the safety assessment are, as a rule, handled sufficiently pessimistically in analyses of radionuclide transport that differences between different fuel types are irrelevant. The material composition of the assemblies is well known and the uncertainties are small, largely since the quality requirements in the fabrication of fuel assemblies are very strict.

Radionuclides are formed during reactor operation by nuclear fission of uranium-235 and plutonium-239 in particular, and by neutron capture by nuclei in the metal parts of the fuel elements. Most of the radionuclides are embedded in the fuel matrix of uranium dioxide. A few fission products are relatively mobile in the fuel and may migrate to the surface of the fuel pellets during operation. The inventory of radionuclides in the fuel at the time of deposition can be calculated with relatively high accuracy. The uncertainty is typically a few tens of percent and is mostly related to the fuel's burn-up and initial enrichment. Uncertainties related to the inventories of higher actinides and some activation products may be higher. The relative differences in radionuclide inventory with respect to burn-up are small. BWR fuel and PWR fuel differ only to a limited degree regarding radionuclide content.

The canister insert is sealed at atmospheric pressure in an atmosphere of at least 90% inert gas and the maximum permissible quantity of water in a canister is 600 grams. This value is equivalent to the void in one fuel rod in each one of the 12 fuel elements in a BWR canister.

Cast iron insert and copper canister

The canister consists of an inner container, the insert of cast iron and an outer shell of copper. The cast iron insert provides mechanical stability and the copper shell protects against corrosion in the repository environment. The copper shell is 50 mm thick and the cylindrical canister has a length of approximately 4.8 metres and a diameter of 1.05 metres. The copper shell is made of pure oxygen-free copper. The insert is cast from spheroidal graphite cast iron and has channels where the fuel assemblies are placed. The uncertainties in material composition are small for the canister materials.

The insert is presently available in two versions: one for 12 BWR assemblies and one for 4 PWR assemblies. A canister holds about two tonnes of spent fuel. Canisters with BWR and PWR assemblies weigh 25 and 27 tonnes, respectively. The decay heat in the spent fuel disposed in one canister is limited to 1,700 W, to fulfil temperature requirements for the bentonite buffer.

Four possible methods for fabrication of the copper tube have been tested by SKB: roll forming of copper plate to tube halves which are welded together, seamless tubes formed by extrusion, pierce and draw processing, and forging. All these methods produce a copper cylinder that must be machined internally and externally as well as on the end surfaces to get the desired dimensions. SKB has selected extrusion as reference method for fabrication of the copper tube and forging for fabrication of the copper lid and bottom. The insert for fuel assemblies are designed to be fabricated by casting. The mass production of the canister parts, i.e. the insert, copper tube, lid, and bottom, may very well be done by different companies applying different methods that all fulfil the set requirements.

Welding of the lid and bottom of the copper canister is done by friction-stir welding (FSW) in the reference case, since this is the preferred alternative according to recent decisions. As an alternative, electron-beam welding (EBW) could be used, but this option is not considered in SR-Can. Radiographic and ultrasonic techniques for non-destructive testing (NDT) of the canisters and welds are being developed.

The fuel will be placed in the canister in the encapsulation plant. The insert will be closed with a lid which is fastened with a bolt. The lid of the copper shell is then attached by welding, and the integrity of the weld is verified by NDT.

A first evaluation of the reliability of the sealing process under normal operation, of its surveillance functions and of the NDT suggests that the likelihood of disturbed operations leading to copper thicknesses below 40 mm is very low.

Buffer

In the deposition holes, the copper canister is surrounded by a buffer of clay. The buffer is deposited as bentonite blocks below and above the canister and rings surrounding the canister. Each bentonite unit is about 500 mm high and has a diameter of 1,650 mm. The thickness of the rings is 315 mm. One block is placed below the canister, rings surround the canister and blocks are placed above the canister.

Two different types of bentonite have been considered as reference buffer material for the purpose of SR-Can. One is a natural Na-bentonite of Wyoming type (MX-80) supplied by the American Colloid Company and the other is a natural Ca-bentonite (Deponit CA-N) from Milos supplied by Silver and Baryte. The bentonite consists mainly of the smectite mineral montmorillonite with the characteristic property that it swells in contact with water. SKB has not made a final selection of a buffer material. The two materials analysed in SR-Can are examples of possible options.

The bentonite, bought in bulk form and transported by ship, is subject to quality control both before loading in the ship and at reception. Quality control is undertaken also during the manufacture of the blocks and rings; one important check is the water content before pressing so that this can be adjusted.

The important overall aim in the manufacture of bentonite blocks and rings and the subsequent deposition process is to achieve a specific final density in the water-saturated buffer. The density requirement for the saturated buffer is 1,950–2,050 kg/m^3. The bulk density is dependent on the annular slots between the canister and buffer and between buffer and rock, left in order to facilitate deposition. The annular slot between the canister side and the buffer is nominally 5 mm wide and that along the circumferential boundary between the buffer and the rock is 30 mm. The slots are left empty. Filling the void with bentonite pellets could limit, but probably not eliminate the effects of thermal spalling as a pellets filled outer void will limit the possibility for fallout of rock pieces in the wall.

Buffer emplacement in a tunnel may take place several months after the drilling of the deposition holes. The deposition holes are assumed to be filled with water in the meantime, which is why draining is the first step in the preparation of the holes. Deposition starts with the hole at the far end of the tunnel. The buffer is put into position by a specially designed buffer filling vehicle. The bentonite lining is thereafter checked. The emplacement of the copper canister is done with a specially designed deposition machine which also places a top bentonite block immediately after the canister is emplaced. The emplacement of the canister will be documented by appropriate safeguards measures in its final position. The final handling procedures and the final design of the buffer filling vehicle and the deposition machine are not yet decided, but do not affect the description of the work procedures. Small geometric tolerances in the deposition holes mean a very small risk for faulty emplacement of the buffer and canister.

The bentonite must be protected from water or high humidity until the tunnel is backfilled. The reason is that the buffer may start swelling before the deposition of the canister and/or before the tunnel backfilling can apply its counterforce on the buffer. One possible method is to insert a drain tube in the deposition hole and to protect the whole buffer with a plastic bag that is kept sealed until the backfilling of the tunnel starts. The plastic bag and drain tube would be removed after use. This methodology has been successfully used in several field test, e.g. the Prototype Repository at Äspö HRL. In SR-Can it is assumed that the removal of these items will be successful in all cases, or that effective remedial action will be taken in the event of failure.

Bottom plate in deposition holes

The bottom of the deposition hole is levelled off with a cast concrete base plate. The base plate serves as a stiff support and the pile of bentonite blocks thereby has a vertical centre line defined, so that the canister can enter gently and the slot between blocks and rock surface is even enough to allow the block lifting tools and the other parts to pass freely.

The thickness of the cast base plate will be adapted to the roughness of the rock and will be about 5 cm at the thinnest part and 10 cm as a maximum. The base plate is to be cast of concrete with low pH cement. The development of suitable cement is in progress. A copper plate, a few millimetres thick, will be placed on the concrete surface to protect the bentonite from being wetted by ground water penetrating the concrete plate. A peripheral gap is to be left between the concrete base plate and the rock wall where ground water can be collected and pumped up from the hole as long as the deposition tunnel is open.

Backfill of deposition tunnels

The extent of this sub-system component is defined in geometrical terms as the deposition tunnel and the upper one meter of the deposition holes. All materials within the tunnel are included i.e. the backfill material itself, grout in grout holes and the relatively limited amounts of structural and stray materials left in the tunnels. Exploratory boreholes and the plug at the end of the deposition tunnel are distinct sub-systems. Grout in rock fractures is associated with the geosphere.

The final decision on excavation technique for the deposition tunnels has not been taken and two possible techniques, drill and blast or mechanical excavation (tunnel boring machine, TBM), are possible options. However, only the drill and blast option is analysed in SR-Can. The excavation technique will have implications on the dimensions, the shape of the deposition tunnels and the extent of the excavation damaged zone in the host rock. The cross section in a drill and blast deposition tunnel is a square with an arched roof.

Two backfill concepts are analysed in SR-Can:

- Precompacted blocks of a natural swelling clay (not necessarily a bentonite). Friedland clay is used as an example of such a material in SR-Can. The whole tunnel is filled with pre-compacted blocks. The gaps between the rock and the blocks are filled with pellets of the same material.
- Precompacted blocks made of a mixture of bentonite of buffer quality and crushed rock with a weight ratio of 30/70. The gaps between the rock and the blocks are filled with bentonite pellets.

Friedland Clay is a natural clay, mainly consisting of mixed layer smectite/illite. The bentonite component in the 30/70 mixture is assumed to have the same composition as the buffer bentonite. The crushed rock is taken from the residues from the excavation of the repository.

The manufacturing of the backfill material will take place in a production facility close to the final repository. Quality control of the composition of the material will take place at different stages: the clay and the rock aggregates will be sampled and analysed before mixing, the composition will be controlled after mixing, and samples will also be taken after emplacement in the tunnel to ensure that the homogeneity is good.

The aim is to limit the amount of construction and stray materials left in the deposition tunnels. Rock supports, mainly rock bolts and reinforcement nets will be left in the tunnels, as they are essential to workers' safety, whereas the other installations and structures, e.g. roadbeds, will be removed before closure of the deposition tunnels.

In SR-Can it is assumed that low pH cement, or other low pH grouting material, will be used for grouting of deposition holes and of deposition tunnels and also for potential shotcreting of deposition tunnels. These low pH materials are expected to have porewaters with pH ≤ 11. The development of low pH materials is ongoing meaning that their final compositions are not available.

Backfill of other repository cavities

The extent of this sub-system is defined in geometrical terms as all rock excavation volumes except those in the deposition tunnels and deposition holes. The definition thus includes the volumes of, e.g. access ramp and shafts, transport and main tunnels, ventilation shafts, and the central area, which together make up the necessary space for access to and operation of the underground facility and its deposition areas.

For the purpose of SR-Can, it is assumed that the same backfill concept will be used in these cavities as in the deposition tunnels. It is further assumed that the same working methods for application and quality control of the backfill are used.

As part of the decommissioning of the facility and as for the deposition tunnels, installations and building components will be stripped out prior to the backfilling of the underground facility. Materials like roadbeds will be removed, whereas rock supports like shotcrete and rock bolts, as well as grout in grout holes, will be left. The final routines for decommissioning and cleaning of the tunnels have not been specified at this stage.

Plugs

Each backfilled deposition tunnel needs to be sealed awaiting the backfilling of the main tunnel. The prime function of the plug is to take the hydraulic gradient from ambient pressure at the level to atmospheric pressure in the open drift system under ground, and by that prevent piping in the backfill. The hydrostatic pressure is the dominating construction requirement. The plug provides a mechanical support to the backfill material and it is sized to be strong enough to withstand the combined pressure from groundwater and the swelling of the bentonite. The plug is also required to prevent water flow. The plugs will be left in the repository at its closure, but they have no long-term safety functions.

The plug considered is a reinforced concrete plug grouted with low pH cement anchored in a slot in the rock. The design considered is similar to the reinforced plugs installed in the Prototype Repository in Äspö HRL.

Borehole seals

A number of more or less vertical surface-based investigation or characterisation boreholes are to be drilled during site investigations in order to obtain, e.g., data on the properties of the rock. These boreholes will be sealed, no later than at the closure of the final repository. Some holes will be bored from the repository tunnels during the construction phase, meaning that horizontal and upwards-directed holes also have to be sealed.

The borehole seals must prevent short-circuiting of flow of potentially contaminated groundwater from the repository. They should, therefore, not be more transmissive than the undisturbed, surrounding rock. Time-dependent degradation must be accepted, but the goal is to use plug materials that maintain their constitution and tightness for a long time.

Seals for boreholes are under development as part of SKB's RD&D programme. The concept adopted for surface-based boreholes in SR-Can comprises the following materials at different depths: compacted till (0–3 m), close-fitting rock cylinders from the site (3–50 m), compacted till (50–60 m), smectite pellets (60–100 m), and highly compacted smectite clay contained in perforated copper tubes (below 100 m). Tunnel-based boreholes are assumed to be filled with highly compacted smectite clay in perforated copper tubes. These boreholes are to be plugged with concrete at the tunnel.

Contents

1 Introduction

Radioactive waste from nuclear power plants in Sweden is managed by the Swedish Nuclear Fuel and Waste Management Co, SKB. Within SKB's programme for the management of spent nuclear fuel, an interim storage facility and a transportation system are today (October 2006) in operation. Several decades of research and development has led SKB to put forward the KBS-3 method for the final stage of spent nuclear fuel management. In this method, copper canisters with a cast iron insert containing spent nuclear fuel are surrounded by bentonite clay and deposited at approximately 500 m depth in saturated, granitic rock. Around 9,000 tonnes of spent nuclear fuel is forecasted to arise from the Swedish nuclear power programme, corresponding to roughly 4,500 canisters in a KBS-3 repository.

Two principal remaining tasks in the programme are to locate, build and operate i) the final repository and ii) an encapsulation plant in which the spent fuel will be emplaced in canisters to be deposited in the final repository.

SKB is currently pursuing site investigations for a final repository in the municipalities of Östhammar (Forsmark area) and Oskarshamn (subareas Simpevarp and Laxemar). The investigations are conducted in two stages, an initial phase followed, if the expected site suitability is confirmed, by a complete site investigation phase. The aim is to build a final repository at one of these candidate sites, provided that the bedrock and other relevant conditions are found suitable. An application to build a final repository will be made at the end of 2009 according to current plans. The initial stage has been completed and SKB has decided to pursue the investigations at the Forsmark site and at the Laxemar subarea at the Oskarshamn site. The Simpevarp subarea has been set aside, since it has been judged to be, albeit suitable from the point of view of long-term safety, less flexible in terms of available space for deposition than the Laxemar subarea.

1.1 SR-Can safety assessment

The SR-Can project is a preparatory stage for the SR-Site assessment, the report from which will be used in support of SKB's application to build a final repository. The purposes of the safety assessment SR-Can are the following:

1. To make a first assessment of the safety of potential KBS-3 repositories at Forsmark and Laxemar to dispose of canisters as specified in the application to build the encapsulation plant.
2. To provide feedback to design development, to SKB's R&D programme, to further site investigations and to future safety assessment projects.
3. To foster a dialogue with the authorities that oversee SKB's activities, i.e. the Swedish Nuclear Power Inspectorate, SKI, and the Swedish Radiation Protection Authority, SSI, regarding interpretation of applicable regulations, as a preparation for the SR-Site project.

As SKB's waste management programme continues, the encapsulation technique will be further developed and selection of materials for buffer and backfill and procedures for manufacturing and deposition of engineered barriers will be further specified. Also, the sites will become progressively better characterised and excavation techniques specified in more detail. Safety assessments at various stages of the programme will draw on the information available at that particular stage. Information on all the components is needed at every stage, since safety depends on all these elements. The focus of a particular assessment will, however, be determined not only by the information available but also by the purpose of the assessment, i.e. the decision or decisions that it is intended to support.

The objective of the SR-Can report is to investigate whether the KBS-3 method has the potential of fulfilling regulatory safety criteria, given the host rock conditions at the sites in so far as they can be specified after the initial site investigation phase. The intention of the SR-Can report is not to fully establish the suitability of the studied sites – this will be done in SR-Site. The intention is also not to finally establish the technical system for disposal – but rather to investigate the safety of the system as it is specified at this stage, and to give feedback for further developments to that specification.

1.2 Initial state

The repository system, broadly defined as the deposited spent nuclear fuel, the engineered barriers surrounding it, the host rock and the biosphere in the proximity of the repository, will evolve over time. Future states of the system will depend on:

- the initial state of the system,
- a number of radiation-related, thermal, hydraulic, mechanical, chemical and biological processes acting within the repository system over time and
- external influences acting on the system.

Which means that a comprehensive description of the initial state of the repository system is one of the main bases for the safety assessment. For the engineered barrier system, the time of deposition is a natural starting point when a specific part of the system is concerned, e.g. an individual deposition hole with its canister and buffer. However, if the entire ensemble of deposition holes is considered, there is no unique time of deposition. Neither is the time of repository closure a suitable choice for the engineered barrier system, since different parts of the repository will, at that time, have reached different stages of e.g. thermal and hydraulic evolution depending on the time of deposition and on spatial variability of rock conditions within the repository. The most reasonable approach is, therefore, judged to be to define the time of the initial state as that of deposition for each deposition hole with its canister, buffer and backfill, and then to describe the common evolution that all deposition holes will go through, taking the spatial variability into account.

The initial state of the engineered parts of the repository system is largely obtained from the design specifications of the repository, including allowed tolerances or deviations. Also the manufacturing, excavation and control methods have had to be described in order to adequately discuss and handle hypothetical initial states outside the allowed limits in the design specifications. The initial state of the spent fuel and engineered parts for SR-Can is compiled in this report.

The initial state of the geosphere and the biosphere is determined by site investigations. Field data from the site investigations are analysed, within the site investigation project, to produce a site descriptive model of the geosphere and the biosphere for the Forsmark and Laxemar sites, as reported in /SKB 2005b/ and /SKB 2006h/, respectively.

1.3 Reference initial state for spent fuel and engineered barriers

The reference initial state of the engineered barriers is defined as the design specifications with tolerances including allowance for deviations according to the manufacturing and control procedures.

The tolerances should in principle be possible to derive or verify from the manufacturing and control procedures employed in the engineering activities. At the current stage of the final repository programme, such procedures have reached varying degrees of maturity. This means that the tolerances are more or less well specified for different aspects of the initial state of the engineered barrier system (EBS). For example, regarding the crucial issue of the quality of the canister seals, SR-Can is based on the tolerances determined from test statistics on a prototype sealing system including non-destructive testing. In other cases, the given tolerances are, at this stage, aims for the design of the production system in question. For example, this is the case for the buffer density. Here, a qualitative description of a tentative manufacturing and control system exists along with preliminary test results, but the data do not allow derivation of a quantified tolerance.

It should also be noted that many parts of the system are as yet not finally designed – there can be many changes in the future. The design and technical solutions presented here are representative of the current stage of development.

Initial state aspects crucial for safety

From earlier safety assessments, and from the general understanding of the repository system, a number of initial state aspects of the engineered barrier system critical to safety have been identified. The analyses conducted in SR-Can will inform an update of this set of critical initial state aspects. From earlier safety assessments, the critical aspects include:

- The residual power of the spent fuel in each canister, affecting the short-term thermal evolution of the repository and in particular the peak temperatures in the near-field: The copper canister tightness, in particular the quality of the sealing welds:
- The strength of the cast iron insert, affected by the quality of the casting process.
- The amount and composition of buffer dry mass emplaced in each deposition hole, affecting the final density of the buffer after water saturation.
- The amount and composition of backfill dry mass emplaced in each deposition tunnel, affecting the final density of the backfill after water saturation.

Format for initial state descriptions

The initial state of each barrier or sub-system is described by a set of physical variables, selected to allow an adequate description of the long-term evolution of the component in question in the safety assessment. The step wise development of the repository and its design means that the degree of knowledge and details in the variables will increase in each step, whereas the uncertainties are expected to decrease.

2 Overview of the engineered part of the repository system

2.1 Introduction

The repository system is based on the KBS-3 method, in which copper canisters with a cast iron insert containing spent nuclear fuel are surrounded by bentonite clay and deposited at 400–700 m depth in saturated, granitic rock, see Figure 2-1.

The facility design with rock caverns, tunnels, deposition positions, etc is based on the design originally presented in the KBS-3 report /SKBF/KBS 1983/, which has since been developed in more detail. The deposition tunnels are linked by tunnels for transport, communication and ventilation. One ramp and five shafts connect the surface facility to the underground repository. The ramp is used for heavy and bulky transports and the shafts are for utility systems and for staff transports. The different parts of the final repository are sketched in Figure 2-2.

For the purposes of the safety assessment, the engineered part of the repository system has been sub-divided into a number of components or sub-systems. These are:

- The fuel, (also including cavities in the canister since strong interactions between the two occur if the canister is ruptured).
- The cast iron insert and the copper canister.
- The buffer in the deposition hole.
- The bottom plate in the deposition hole.
- The deposition tunnel with its backfill material.
- Other repository cavities with their backfill materials, e.g. transport tunnels, shafts and central underground area.
- Repository plugs.
- Investigation boreholes with their sealing material.

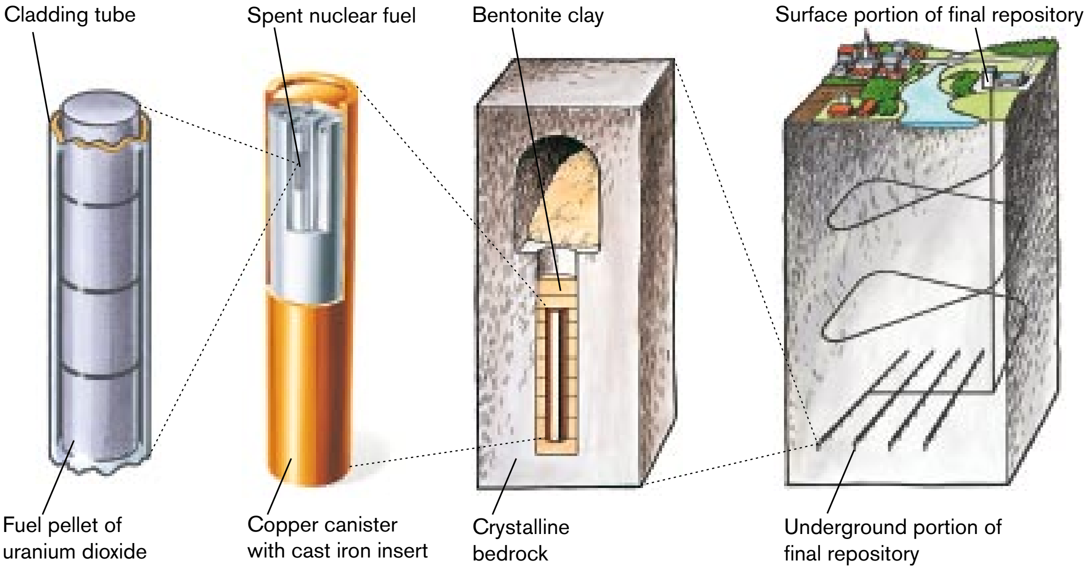


Figure 2-1. The KBS-3 method for disposal of spent nuclear fuel.

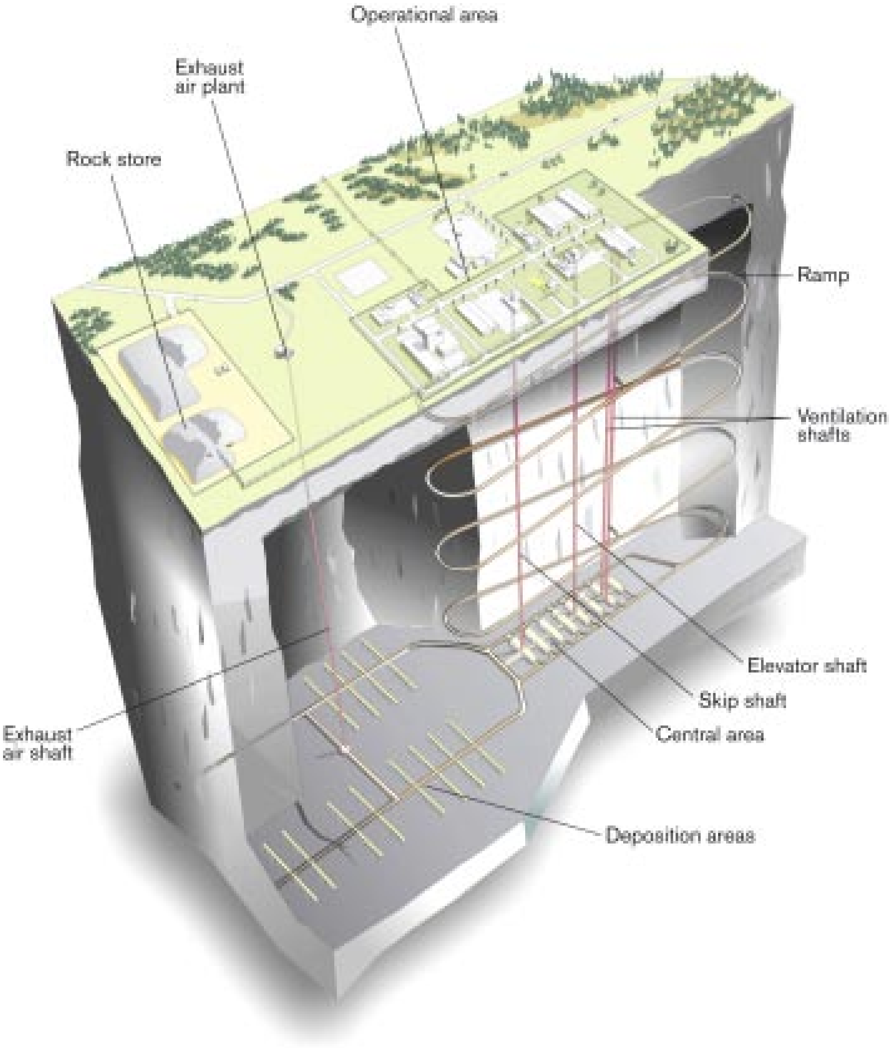


Figure 2-2. *Generic example of repository layout.*

This particular sub-division is dictated by the desire to define components that are as homogeneous as possible without introducing an unmanageable multitude of components. Homogeneity facilitates both characterisation of a component and the structuring and handling of processes relevant to its long-term evolution. Also, the importance of a particular feature for safety has influenced the resolution into components. In principle, components close to the source term and those that play an important role for safety are treated in more detail than peripheral components.

2.2 Deep repository for spent fuel

Around 9,000 tonnes of spent nuclear fuel is forecasted to arise from the Swedish nuclear power programme /SKB 2005a/, corresponding to roughly 4,500 canisters in the repository. These figures are based on an assumed reactor operational time of 40 years. To allow for uncertainties in the future Swedish nuclear power programme, the SR-Can assessment will analyse a repository with 6,000 canisters, thus, corresponding to around 12,000 tonnes of fuel.

2.2.1 Generic repository layouts

The recommendation for the layout of the deep repository is to use a ramp combined with a skip shaft and preferably having only one operational area /Bäckblom et al. 2003/. The layout also includes shafts for passenger lifts and ventilation air. The main advantage with this arrangement is that the ramp is used only for a small number of transports, namely transport casks, buffer material and some bulky or heavy building material, while the skip is used for frequent transports of excavated rock and backfill material. In that way, the risk for fires or accidents in the ramp is greatly reduced. Another advantage is that excavation work to a great extent can be separated from deposition work. If excavation of the skip shaft and the ramp will be started at the same time, it is also possible to reduce the time needed for construction. Figure 2-2 shows a generic repository layout.

SKB is performing site investigations in two municipalities, Oskarshamn and Östhammar. Site descriptive models are developed and the site specific designed repository layouts (version D1) evaluated for the potential repository sites at Forsmark in Östhammar and Laxemar in Oskarshamn are analysed in SR-Can. The repository is located at –400 m level in Forsmark and at –500 m level in Laxemar.

Based on the design specifications of a KBS-3 repository /SKB 2004b/, the facility descriptions from the previous design step (Layout E) /SKB 2002/ and the site descriptive model version 1.2 for Forsmark and Laxemar respectively /SKB 2005b, SKB 2006h/, a site specific layout (Layout D1) for surface and underground facilities was developed. In principle, the analyses followed the model described in the design premises /SKB 2004b/. One important purpose with the design work at this stage is to show that the repository will fit into the target area at the site. The main uncertainties related to the size of the deposition area are connected to the Swedish program for nuclear energy production, i.e. the total number of canisters and the quality of the rock and fracture zones influencing the selection of canister positions in the repository.

Major prerequisites for the layout of the underground facility have been:

- The layout has about 6,000 canister positions.
- The maximum length of the deposition tunnels is 300 m, compared with 265 in the generic arrangement.
- The deposition tunnels should be separated by 40 m. Excavation, deposition of canisters, backfilling, plugging and investigations shall be run in parallel.
- Evacuation of main and transport tunnels shall be possible in two directions.

2.2.2 Site specific repository layouts

Forsmark

Four different layouts were worked out at two different levels (–400 and –500 m respectively) and with two different solutions for the operational area (one or two operational areas) /Brantberger et al. 2006/. The layout analysed in SR-Can is located at –400 m level and has one operational area, see Figure 2-3. The deep repository should be located in the northern part of rock domain 29.

An important conclusion from rock mechanical analyses is that the orientation of the deposition tunnels should be parallel or only slightly inclined to the maximum horizontal principal stress. Deformation zones and associated respect distances had a great influence on the layout. When developing the layout shown in Figure 2-3 stochastically generated fracture zones with a radius larger than 100 m were considered and the total portion of abandoned deposition holes was 11%. The distance between the deposition holes are 6 m.

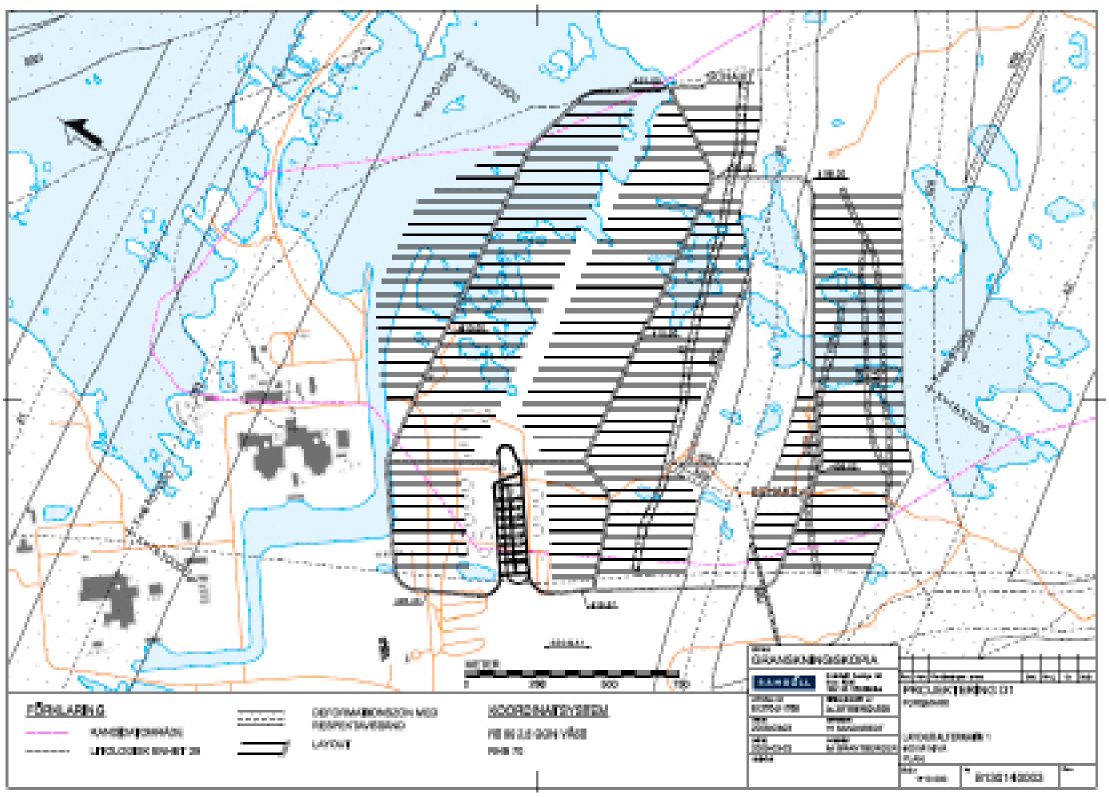


Figure 2-3. Potential repository layout at the –400 m level in Forsmark, from /Brantberger et al. 2006/.

Laxemar

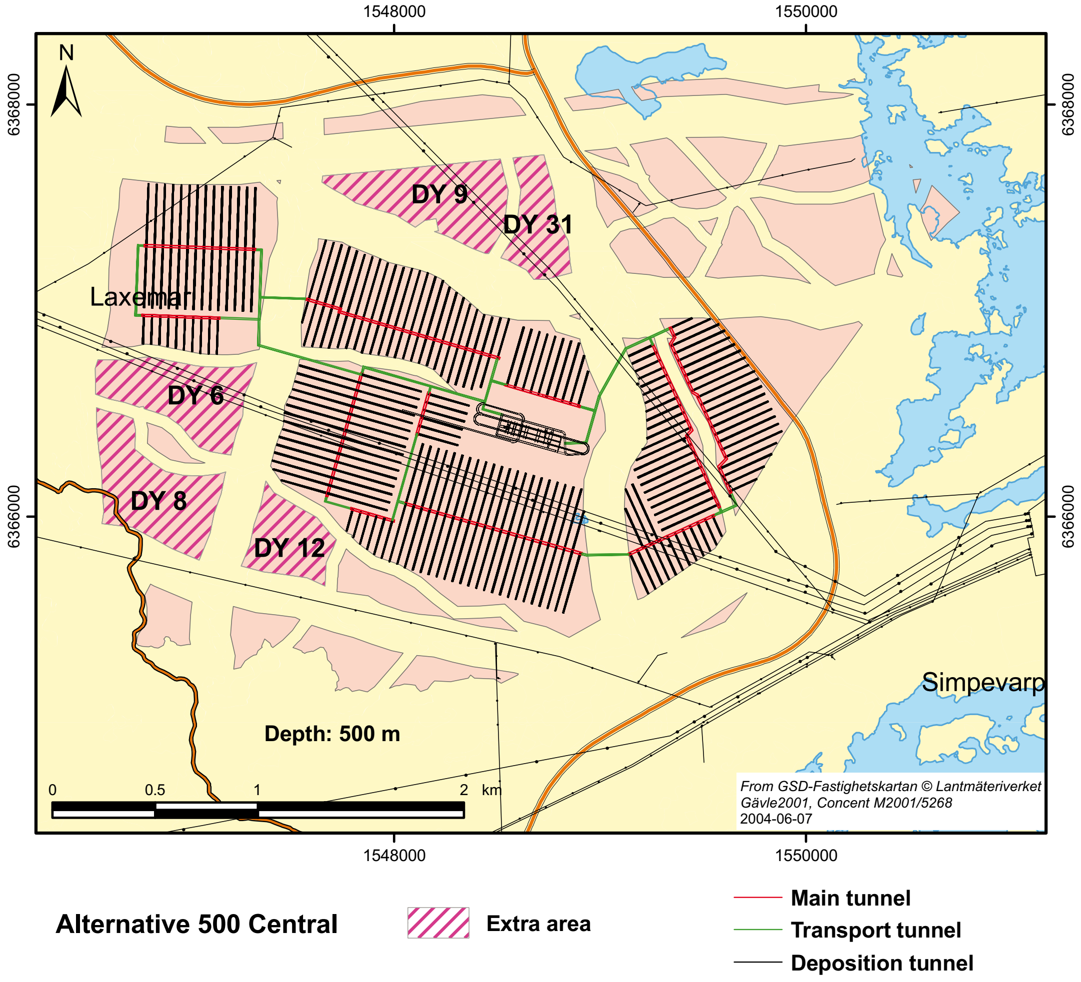
Four different layouts were worked out at two different levels (–500 and –600 m, respectively) and with two different solutions for the operational area /Janson et al. 2006/. The layout analysed in SR-Can in located at –500 m level, see Figure 2-4, and has a central location of the operational area.

The orientation of the deposition tunnels is, at this design stage (D1), based only on the geometrical prerequisites while other issues, e.g. water inflow, rock stability and stresses were disregarded. This could be done since the differences between possible orientations were assessed to be small. The distances between the deposition holes are 7.2 or 7.4 m and the total portion of abandoned deposition holes are 20%.

2.3 Repository sub-systems

Fuel/cavity in canister

This sub-system comprises the spent fuel in the canister and the cavity in the canister. Several types of spent fuel are to be deposited in the repository. For the option with 40 years of reactor operation, the quantity of BWR fuel is estimated at 7,000 tonnes and the quantity of PWR fuel at 2,300 tonnes /SKB 2005a/. In addition, 23 tonnes of MOX fuel and 20 tonnes of fuel from the reactor in Ågesta will be deposited. To allow for uncertainties in the future Swedish nuclear power programme, the SR-Can assessment will analyse a repository for around 12,000 tonnes of fuel, thus, corresponding to 60 years of reactor operation. The fuel burn-up can vary from approximately 15 to 60 MWd/kgU /SKB 2004a/.



From GSD-Fastighetskartan © Lantmäteriverket Gävle2001, Concent M2001/5268
2004-06-07

Figure 2-4. *Potential repository layout at –500 m level in Laxemar, from /Janson et al. 2006/.*

Cast iron insert and copper canister

SKB's reference canister is 4.8 m long and has a diameter of 1.05 m. The canister shall be intact at deposition, it shall be resistant to the chemical environment in the deep repository and it shall withstand the mechanical loads. The canister consists of an insert of cast iron and a copper shell. The cast iron insert provides mechanical strength and the copper shell protects against corrosion in the repository environment. The insert has channels in which the spent fuel assemblies are placed and is available in two versions, one for twelve BWR assemblies and one for four PWR assemblies. A canister holds approximately 2 tonnes of spent fuel. The canisters with BWR and PWR assemblies weigh 25 and 27 tonnes, respectively. The decay heat in the spent fuel disposed in one canister is limited to 1,700 W, to fulfil temperature requirements for the bentonite buffer.

The spent nuclear fuel forecasted to arise from the Swedish nuclear power programme /SKB 2005a/, corresponding to roughly 4,500 canisters in the repository. These figures are based on an assumed reactor operational time of 40 years. To allow for uncertainties in the future Swedish nuclear power programme, the SR-Can assessment analyses a repository with 6,000 canisters, thus, corresponding to around 12,000 tonnes of fuel.

Buffer

In the deposition holes, the copper canister will be surrounded by a buffer of clay. The buffer is supposed to protect the canister. SKB has not made a final choice of buffer material and two different types of bentonite are selected as reference materials in SR-Can. One is a natural sodium bentonite from Wyoming (MX-80) and the other is a natural calcium bentonite from Milos (Deponit CA-N). The buffer is deposited as bentonite blocks below and above the canister and rings surrounding the canister.

Bottom plate in the deposition holes

The bottom of the deposition hole will be levelled off with a cast concrete plate. The bottom plate forms a stable foundation for the bentonite blocks and rings in the deposition hole. The final layout of the plate has not been decided, here the plate is assumed to have a thickness of 5 to 10 cm. The bottom plate is to be cast of concrete with low pH cement. A copper plate, a few millimetres thick, will be placed on the concrete surface to protect the bentonite from being wetted by ground water penetrating the concrete plate.

Backfill of deposition tunnel

The extent of this sub-system component is defined in geometrical terms as the deposition tunnel and the upper one meter of the deposition holes. All materials within the tunnel are included i.e. the backfill material itself, grout in grout holes and the relatively limited amounts of structural and stray materials left in the tunnels. Grout in rock fractures is associated with the geosphere.

The final decision on excavation technique for the deposition tunnels has not been taken and two possible techniques, drill and blast or mechanical excavation (tunnel boring machine, TBM), are still possible options. However, only the drill and blast option is analysed in SR-Can. The cross section of the deposition tunnels is mainly depending on the size of the deposition machine. With the present design of the deposition machine, the cross-section of the deposition tunnel is 4.9 m wide and 5.4 m high with a curved roof.

After deposition of the buffer and the canisters in one deposition tunnel, the tunnel will be backfilled with a material adapted to the chemical conditions at the selected site. Two backfill concepts are analysed in SR-Can. Both concepts comprise placement of prefabricated blocks of backfill in the tunnel. The blocks are either made of a mixture of 70 wt-% crushed rock and 30 wt-% bentonite or of blocks made of 100% natural Friedland clay. The slots between the rock and the blocks are filled with pellets of either bentonite or Friedland clay.

Backfill of other repository cavities

Repository cavities other than deposition tunnels will be backfilled at the closure of the repository. Theses cavities, e.g. access ramp, shafts, central area, main and transport tunnels can be backfilled with the same material as the deposition tunnels but other materials, e.g. crushed rock and rock masses are considered. SKB has not made a final choice of backfill material. For the purpose of SR-Can, it is assumed that the same backfill concept will be used in these cavities as in the deposition tunnels.

Plugs

Three types of plugs may be used in the repository: deposition tunnel plugs, plugs with a permanent function and plugs for preventing human intrusion after final sealing and closure of the repository. The deposition tunnel plugs will be installed at the end of a backfilled deposition tunnel to allow early saturation of the backfill material. These plugs will be left in the repository at backfilling of transport tunnels and other cavities but they are not credited with any function with regard to long-term safety.

Permanent plugs, e.g. between deposition areas, with a long-term safety function are considered as a possibility. When it comes to final sealing and closure of the repository the third types of plugs will be installed, with the main aim to prohibit unwanted intrusion. The design of such plugs is not the subject of the present assessment.

Borehole seals

Investigation boreholes will be drilled from the surface during site investigations and from the tunnels during detailed characterisation and repository construction. These boreholes have to be sealed no later than at closure of the repository. The concept adopted for surface-based boreholes in SR-Can comprises the following materials at different depths: compacted till (0–3 m), close-fitting rock cylinders from the site (3–50 m), compacted till (50–60 m), smectite pellets (60–100 m), and highly compacted smectite clay contained in perforated copper tubes (below 100 m). Tunnel-based boreholes are assumed to be filled with highly compacted smectite clay in perforated copper tubes. These boreholes are to be plugged with concrete at the tunnel.

Principal data for the underground facility

The estimated excavated volumes at the two sites are summarised in Table 2-1 and the estimated amounts of materials in the repository at closure are given in Table 2-2.

Table 2-1. Data for the underground facilities at Forsmark and Laxemar, respectively (6,000 canisters).

	Width (m)	Height (m)	Total volume (m^3)	
			Forsmark	Laxemar
Deposition tunnels	4.9	5.4	1,306,000	1 667,000
Main tunnels	10	7	388,000	430,000
Transport tunnels	7	7	145,000	213,000
Ramp	5.5	6	145,000	182,000
Central area	3–14	3–16	154,000	154,000
Shafts	2.5–5.5	–	33,000	41,000
Total			2,170,000	2,690,000

Table 2-2. Summary of materials in the repository – estimated amounts (6,000 canisters).

Deposition tunnels	Amount (tonnes)	Amount (tonnes)
Engineered barriers		
Canister	126,000	126,000
Bentonite buffer	132,000	132,000
Bottom plate in deposition holes (concrete)	3,100	3,100
Backfill in deposition tunnels	2,500,000	3,100,000
Backfill in other cavities	1,600,000	1,900,000
Structural materials		
Rock bolts (steel)	700–1,000	1,100–1,400
Nets		400–540
Anchoring grout for rock bolts	200–300	780–1,300
Grout in injection holes	50–600	1,600–3,400

3 Fuel/cavity in canister

3.1 General

This repository sub-system comprises the spent fuel and the cavity in the canister. The total quantity of spent fuel obtained from the Swedish nuclear reactors will depend on operating time, energy output and fuel burn-up. The planning for the Swedish nuclear fuel system is based on a reference scenario with an operation time of 40 years for the reactors that are currently in operation. Barsebäck 1 was taken out of operation in November 1999 and Barsebäck 2 in May 2005. At the end of 2005 approximately 6,300 tonnes of spent fuel have been generated /SKB 2005a/. The total quantity of spent fuel can be estimated at 9,300 tonnes for the reference scenario for the nuclear fuel system /SKB 2005a/.

Fuel types

Several types of fuel are to be emplaced in the repository. For the reference scenario with 40 years of reactor operation, the fuel quantity from boiling water reactors, BWR fuel, is estimated at 7,000 tonnes, while the quantity from pressurized water reactors, PWR fuel, is estimated at about 2,300 tonnes /SKB 2005a/. In addition, 23 tonnes of mixed-oxide fuel (MOX) with German origin from BWR and PWR reactors as well as 20 tonnes of fuel from the decommissioned heavy water reactor in Ågesta will be deposited. The total amount of spent fuel and the total number of fuel elements are given in Table 3-1. To allow for uncertainties in the future Swedish nuclear power programme, the SR-Can assessment will analyse a repository with 6,000 canisters, thus, corresponding to around 12,000 tonnes of fuel.

The fuel burn-up is expected to vary from about 15 up to 60 MWd/kg U /SKB 2004a/. The average burn-up for Swedish nuclear fuel (UOX) is currently just above 30 MWd/kg U, but the average burn-up has gradually increased and will be in the range 40–50 MWd/kg U in newer fuel. The burn-up distribution of the fuel in the interim storage Clab in June 2005 is given in Figure 3-1.

The MOX fuel in Clab has an average burn-up of 31 MWd/kgHM and a higher Pu content than UOX fuel due to its relatively low burn-up (about 2.7%). The Ågesta fuel is heavy water reactor fuel. At present there are 222 fuel elements in Clab. The majority of those (about 70%) contain natural uranium; the remainder are enriched to 1.35% (one element contains 2.2% U-235). The burn-up ranges from 0 to 10 MWd/kgU. The existing MOX fuel and MOX fuel that may be used in BWRs in the future is not included in the SR-Can assessment. These fuels will be considered in SR-Site.

Table 3-1. Amount of spent fuel and number of fuel elements.

Fuel type	Scenario with 40 years of reactor operation /SKB 2005a/	
	Spent fuel (tonnes of U)	Number of fuel elements/units
BWR	7,038	38,740
PWR	2,310	5,000
MOX, Ågesta, Studsvik	23+20+2.4	640

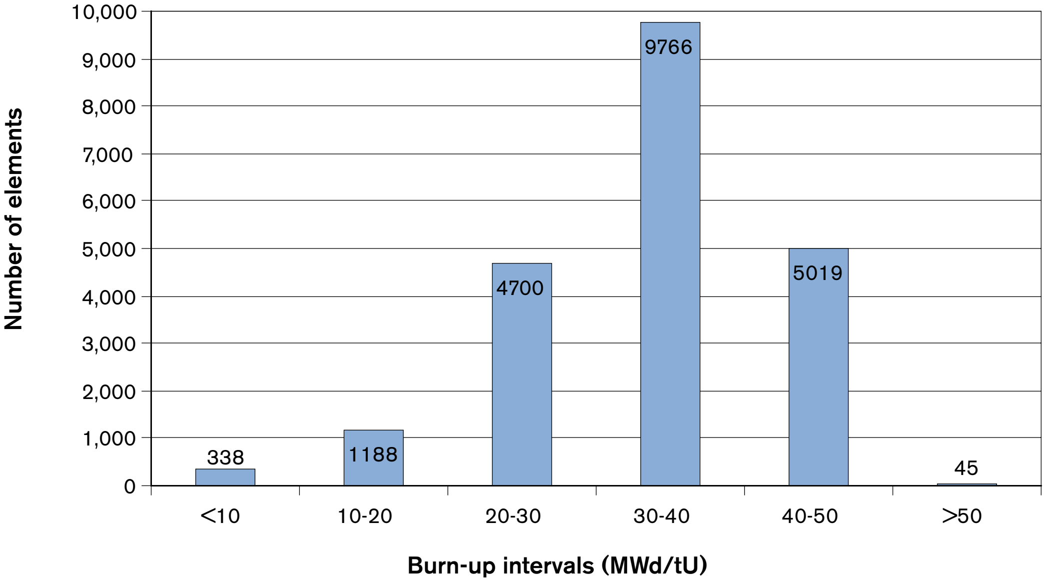


Figure 3-1. *Burn-up distribution in the fuel in the interim storage Clab (30 June 2005).*

Structure of the fuel assemblies

Nuclear fuel, here exemplified by BWR fuel, consists of cylindrical pellets of uranium dioxide. The pellets are approximately 1 cm in diameter and 1 cm in length. They are stacked in approximately 4-metre-long cladding tubes of Zircaloy, a durable zirconium alloy. The tubes are sealed with welds and bundled together into fuel assemblies. The fuel assemblies for a Swedish BWR reactor consist of 64 to 100 rods, arranged in a square array of 8×8 or 10×10 rods. These are, in turn, enclosed by a square fuel channel with a cross-sectional area of approximately 14×14 cm^2. The total length of a BWR assembly can be up to 4.4 m. The length of the column of nuclear fuel is approximately 3.7 m. The fuel assembly components are made of the nickel alloys Inconel and Incoloy, and of stainless steel. Pellets in a cladding tube and a fuel assembly are shown in Figure 3-2.

In the case of the PWR fuel, the array of fuel rods in a fuel assembly is 15×15 or 17×17, giving a cross-sectional area of 21.4×21.4 cm^2. A PWR fuel assembly lacks a fuel channel and is also approximately 10 cm shorter than a BWR assembly.

Aspects of importance in the safety assessment, for example geometrical aspects of the fuel cladding tubes, are handled so pessimistically in analyses of radionuclide transport that differences between different fuel types are irrelevant.

Decay heat

The amount of fuel that can be stored in each canister is dependent on the requirement set that the decay heat in a canister may not exceed 1,700 W. Administrative routines and potential verifying measurements are being developed to ensure that this requirement can be fulfilled for each canister.

The fuel enrichment is reported and the fuel burn-up is calculated and reported by the energy producers. From this data the decay heat in each fuel element can be calculated and an optimisation of the loading of fuel elements into different canisters can be started early. Methods to measure the decay heat of the fuel-elements are available. These methods are calorimetric and, unfortunately, very time consuming. A new method is being developed and it is a hope that this method, gamma-scanning of the fuel assemblies and determination of Cs-137, can be used as verification prior to the emplacement in the canister.

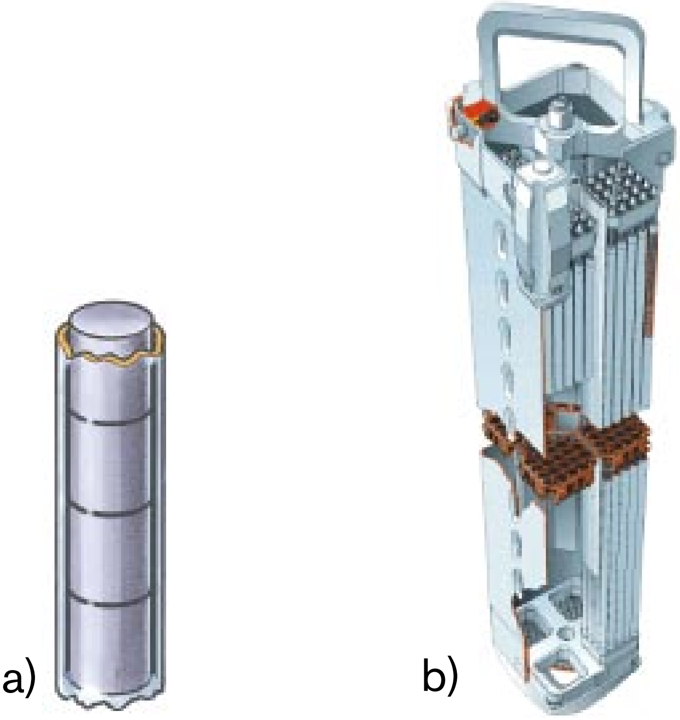


Figure 3-2. a. Cylindrical fuel pellets in cladding tubes of Zircaloy. The pellets have a diameter of approximately one centimetre. b. Fuel assembly of type Svea 96. The assembly consists of 96 fuel tubes and has a height of approximately 4 m.

Radionuclides

Radionuclides are formed during reactor operation by nuclear fission of uranium-235 and plutonium-239 in particular, and by neutron capture by nuclei in e.g. the metal parts of the fuel. The former are called fission products, the latter activation products. Moreover, uranium can form plutonium and other heavier elements by absorbing one or more neutrons. These and other elements (including uranium) are called actinides and decay to radioactive actinide daughters in several steps, finally forming stable isotopes of the metals lead or bismuth.

Most of the radionuclides are embedded in the fuel matrix of uranium dioxide. However, a fraction of the nuclides are relatively mobile in the fuel and may have migrated to the surface of the fuel pellets during operation. These nuclides are located at the grain boundaries and at the fuel clad gaps.

Cavity in canister

This repository sub-system comprise the spent fuel but also the cavity in the canister. The atmosphere in the cavity is water vapour and inert gas e.g. argon. The water originates from defect fuel rods and the inert gas is injected prior to the sealing of the canister.

3.2 Variables

3.2.1 Overview

The spent fuel is described by means of a set of variables, see Table 3-2, which together characterise the spent fuel in a suitable manner for the safety assessment. The description applies not only to the spent fuel itself, but also the cavities in the canister.

Table 3-2. Variables for fuel/cavity in canister.

Variable	Definition
Geometry	Geometric dimensions of all components of the fuel assembly, such as fuel pellets and Zircaloy cladding. Also includes the detailed geometry, including cracking, of the fuel pellets.
Radiation intensity	Intensity of α-, β-, γ- ,and neutron radiation as a function of time and space in the fuel assembly.
Temperature	Temperature as a function of time and space in the fuel assembly.
Hydrovariables (pressure, volume and flows)	Flows, volumes and pressures of water and gas as a function of time and space in the cavities in the fuel and the canister.
Mechanical stresses	Mechanical stresses as a function of time and space in the fuel assembly.
Radionuclide inventory	Occurrence of radionuclides as a function of time and space in the different parts of the fuel assembly. The distribution of the radionuclides in the pellets between matrix and surface is also described here.
Material composition	The materials of which the different components in the fuel assembly are composed, excluding radionuclides.
Water composition	Composition of water (including any radionuclides and dissolved gases) in the fuel's and canister's cavities.
Gas composition	Composition of gas (including any radionuclides) in the fuel's and canister's cavities.

The fuel and the cavity in the canister is characterised with respect to radiation by the intensity of α-, β-, γ- and neutron radiation and thermally by the temperature. Hydraulically, it is interesting to characterise the cavity only if the copper canister should be damaged and water should enter. The cavity is then characterised by water flows and water pressures as well as by gas flows and gas pressures, which are jointly termed hydro-variables. Mechanically, the fuel is characterised by stresses in the materials, and chemically by the material composition of the fuel matrix and metal parts, as well as by the radionuclide inventory. The gas composition and, if water enters the canister, the water composition are also relevant for the description.

The initial state, i.e. the initial values of these variables including allowed variances and tolerances, is described below. Information on variability in spent fuel characteristics between canisters (geometry, inventory, material composition, radiation intensity) cannot be presented at this stage. The final requirements and the routines for how fuel elements will be selected are not worked out at this stage.

3.2.2 Geometry

Initial value

Detailed dimensions for the BWR and PWR reference fuels are found in data sheets, from the fuel suppliers, in Appendix 1. The Zircaloy cladding tube can act as a barrier to radionuclide transport if it is intact. This means that it is of interest to know how many fuel rods have defective cladding tubes at deposition. Approximately 0.004% of the rods in the interim storage (Clab) is defective, 1,000 defective rods of a total of 2.5 million (May 2006).

Uncertainties

The geometric dimensions of the fuel assemblies are very well known. After encapsulation, the fuel will be exposed to high temperatures and the number of clad defects may then increase. The present conclusion is, however, that there is no reason at present to assume that the geometry of the fuel will undergo decisive changes over long periods of time.

3.2.3 Radiation intensity

Initial value

Radiation intensity is reported in the form of dose rates. The dose rate from α- and β- radiation is totally dominant in the fuel pellets and in the fuel-clad gap. Outside the Zircaloy cladding, γ- and neutron radiation dominate.

The dose rate on the surface of a fuel pellet has been estimated /Eriksen et al. 1995/. Based on these results, the surface dose rate at the time of deposition, approximately 40 years after discharge from the reactor, can be estimated at about 700 Gy/h. The contribution from β-radiation is approximately 15%. The estimate applies to PWR fuel with a burn-up of 40 MWd/kg U.

At the same time, the γ- and neutron dose rates at a distance of one metre from two tonnes of unshielded fuel (i.e. the contents of one canister) are 130,000 and 5 mGy/h, respectively (38 MWd/kg U BWR) /Hedin 1997/.

Uncertainties

The radiation dose rate is dependent on the radioactivity, i.e. the radionuclide inventory, and the fuel's geometry. Both of these variables are relatively well-known, and the dose rate can be calculated with sufficient accuracy for the needs of the safety assessment.

3.2.4 Temperature

Initial value

The temperature on the surface of the fuel at deposition is dependent on the decay heat, the thermal properties of the cast iron insert and copper canister, and the external cooling of the canister. The decay heat is well known, while the other factors are more difficult to estimate before all steps in the handling sequence have been established in detail. It is estimated that the temperature will be somewhere between 200 and 400°C /Bjurström and Bruce 1997, 1998/.

Uncertainties

As seen above, the uncertainties are great. However, the temperature lies in a range where the integrity of the fuel is not threatened, and the uncertainty in the temperature is, therefore, unimportant for post-closure safety.

3.2.5 Hydrovariables (pressures, volumes and flows)

Initial value

The hydrovariables are not relevant to describe initially. The gas pressure is discussed in Section 3.2.10.

3.2.6 Mechanical stresses

Initial value and uncertainties

The fuel pellets have inherent stresses caused by cracking etc as a consequence of nuclear fissions and irradiation. The internal structure of the fuel pellets is changed during irradiation depending on temperature and burn-up. Fuel rods and structural elements have inherent stresses due to pressure from fission gases and gas filling. These stresses vary with the make and burn-up of the fuel. The stress distribution in the assemblies is affected in an unpredictable manner by irradiation in the reactor due to the fact that irradiation sometimes causes growth/swelling of the structural materials and due to the fact that stress relaxation varies depending on local temporal variations in temperature.

These stresses have no consequence for the safety assessment.

3.2.7 Radionuclide inventory

Initial value

The inventory of radionuclides in the fuel is calculated and reported as the activity per tonne of fuel in the assemblies. The radionuclide inventories in BWR and PWR fuel at two different burn-ups (38 and 55 MWd/kg in BWR, 42 and 60 MWd/kg in PWR) 40 years after discharge from the reactor were reported in SR 97 /SKB 1999, Håkansson 2000/. No additional calculations of the radionuclide inventory have been performed within the SR-Can project for the spent fuel. The radionuclide inventories are given in the SR-Can data report /SKB 2006g/.

Distribution of radionuclides

For some radionuclides, part of the inventory accumulates on the surface of the fuel pellets and thereby becomes more accessible for transport. The portion and distribution of radionuclides available for instant or rapid release have been estimated /Werme et al. 2004, Johnson and Tait 1997/ and are given in the SR-Can data report /SKB 2006g/.

The portion of the radionuclide inventory that is present in the structural parts of the fuel was reported in /SKB 1999, Håkansson 2000/. The fraction of radionuclides present in the structural parts is also relatively readily accessible for transport.

Uncertainties

The inventory of radionuclides in the fuel at the time of deposition can be calculated with relatively high accuracy. The uncertainty is typically a few tens of percent and is mostly related to the fuel's burn-up and initial enrichment. Uncertainties related to the inventories of higher actinides and some activation products may be higher. The relative differences in radionuclide inventory with respect to burn-up are small. The BWR and PWR fuel differs only to a limited degree regarding radionuclide content.

Very few data are available for the instant or rapid release fraction of the radionuclides (IRF). The best data come from experimental studies of CANDU fuel /Stroes-Gascoyne 1996/. High burn-up is one factor that contributes to a large IRF, but the linear power rating of the fuel seems to be more important. These uncertainties are further discussed in SR-Can data report /SKB 2006g/ and is also discussed further in /Werme et al. 2004/.

Values for the above mentioned data with uncertainties including e.g. deviations in inventory and deviating or damaged fuel are not considered in the SR-Can reporting.

3.2.8 Material composition

Initial value

The materials of the reference fuel assemblies (BWR and PWR) are given in Appendix 1.

Uncertainties

The uncertainties in material composition are small, largely since the quality requirements in the fabrication of fuel assemblies are very strict.

3.2.9 Water composition

Initial value

The temperature and pressure in the cavities in the fuel and canister at deposition are such that water occurs in vapour form, see gas composition below.

3.2.10 Gas composition

Initial value

Fuel-clad gap

The fuel rods are filled with helium to a pressure of 0.4 MPa in fabrication. There are also fission gases from operation, of which mainly Kr-85 is left at the time of deposition.

Canister cavity

The canister insert will be sealed at atmospheric pressure (inert gas), which means that the pressure in the canister cavity may be a couple of atmospheres if the initial temperature is as high as 400°C. Water vapour: The maximum permissible quantity of water in one canister is now set to 600 grams.

Uncertainties

The uncertainties in pressure stem mainly from the uncertainties in temperature. Possible variations are of no importance for post-closure safety.

The maximum permissible quantity of water was earlier set to 50 grams but is now set to 600 grams. The assumption is that one zircaloy cladding per fuel bundle is defected and contains a water volume corresponding to the void volume (50 cm^3) inside a BWR fuel rod. This means that there can be up to 12 defected fuel rods in a canister. This is a very pessimistic estimate of the number defect fuel rods. At present, this assumption will not be treated probabilistically. The consequence of the additional amount of water is that the atmosphere in the canister of air and water vapour has to be replaced with inert gas and water vapour.

4 Cast iron insert and copper canister

4.1 General

The canister consists of an insert of cast iron and an outer shell of copper, Figure 4-1. The cast iron insert provides mechanical strenght and the copper shell protects against corrosion in the repository environment. The cylindrical reference canister has a length of approximately 4.8 m and an outer diameter of 1.05 m. Its copper shell is 5 cm thick. The insert has channels where the fuel assemblies are placed and is available in two versions: one for 12 BWR assemblies and one for 4 PWR assemblies. Canister with BWR and PWR assemblies weigh 25 and 27 tonnes, respectively. The other fuel types can be placed in either of the versions.

A canister holds about two tonnes of spent fuel. The total number of canisters forecasted to arise from the Swedish nuclear power programme is 4,500. This figure is based on an assumed reactor operational time of 40 years. To allow for uncertainties in the future Swedish nuclear power programme, the SR-Can assessment will analyse a repository with 6,000 canisters.

The decay heat in the spent fuel disposed in one canister is limited to 1,700 W, to fulfil temperature requirements for the bentonite buffer.

Fabrication of canister and encapsulation

Four possible methods for fabrication of the copper tube have been evaluated and tested by SKB, roll forming of copper plate to tube halves which are welded together, seamless tubes by extrusion, pierce and draw processing, and forging. All these methods produce a copper cylinder that must be machined internally and externally as well as on the end surfaces to get the desired dimensions. SKB has selected extrusion as reference method for fabrication of the copper tube and forging for fabrication of the copper lid and bottom /SKB 2006a/, see Figure 4-2.

5 cm copper

Estimated weight (kg):	
Copper canister	7,400
Insert	13,600
Fuel assemblies (BWR)	3,600
Total	24,600

Figure 4-1. *Copper canister with cast iron insert.*

Figure 4-2. Canisters parts, cast iron insert, copper tube and lid. A short section of a canister with insert is also shown.

The stock material in fabrication of the copper cylinder by extrusion is a cylindrical ingot. The ingot is piercing pressed to get a good symmetry before it is extruded. The extruded tube is let cooled in a hanging position to get is straightness. The cylindrical shape and the straightness of the tube can be corrected after the hot forming by straightening. Finally the tube is machined to the right shape and size.

Lids and bottoms of copper are machined to the desired dimensions from hot forged blanks. This method reduces the quantity of material that needs to be machined and the hot working gives the material the desired micro structure.

The insert for fuel assemblies are designed to be fabricated by casting. For practical reasons, the fuel channels in the insert are formed with the aid of square steel tubes that are embedded in the casting /Andersson et al. 2004/. The square tubes are welded together to a cassette. The cassette is designed in such a way that the inserts are cast with an integral bottom. The cassette is placed in the mould and before casting the square tubes have to be filled with compacted sand. This is necessary so that the walls of the steel tubes will not be deformed inward by the pressure from the molten metal during casting. The mould can be filled with spheroidal graphite iron either from the top straight down into the mould (top pouring) or by means of bottom pouring, where the molten metal is poured through a runner down to the bottom of the mould and then rises upwards inside the mould. Both these methods have been tested in the casting of inserts and no significant difference between the methods in the quality of the cast inserts has been observed this far. The insert is left in the mould to cool and is thereafter taken out and cleaned. The straightness of the channels is checked and finish machining before the insert is ready to be lowered into a copper tube with welded-on bottom.

The mass production of blanks of the canister parts, i.e. the insert, copper tube, lid, and bottom, may very well be done by different sub-contractors applying different methods that all shall fulfil set requirements. SKB plan to build a canister factory to which the blanks are delivered from the different sub-contractors. The components will be finish-machined, the copper bottom welded to the cupper tube, inspected and assembled at the factory.

Welding of the copper lids and bottoms of the canister can be done either by friction stir welding (FSW) or by electron beam welding (EBW). Both methods have been developed and demonstrated at the Canister Laboratory in Oskarshamn. The demonstrations have showed that FSW full fill the requirements and friction stir welding was selected as SKB's reference method in May 2005 /SKB 2006b/.

Methods for non destructive testing (NDT) of the canister parts (copper cylinder, copper bottom, insert, insert lid, and copper lid) and the welds are being developed. Applied methods for this are radiographic and ultrasonic techniques /SKB 2006c/. After approved inspection the canister parts, the copper cylinder and its bottom, are welded together, the weld is inspected and approved, and the copper shell and the insert are assembled. The empty canister and the copper and insert lids are thereafter delivered to the encapsulation plant.

The fuel will be placed in the canister in the encapsulation plant. The atmosphere in the insert is 90% argon (or other inert gas) and the insert will be closed with an O-ring-sealed lid which is fastened with a bolt. The copper shell's lid is then attached by welding with FSW, and the integrity of the weld is verified by NDT.

Quality control

A quality and environmental management system for the trial fabrication of canisters have been developed at SKB. It is being used in the trial fabrication of canister components and is improved and updated when needed. The aim is to develop the management systems so that it can be used also at regular canister manufacturing and encapsulation and that it will cover the entire chain from material suppliers to delivery of finished canisters. The management system comprises technical specifications, drawings, routines and a quality plan. The canister parts are inspected and tested due to e.g. size, shape, and tolerances. Other parameters have more complex criteria for acceptance e.g. the occurrence of discontinuities. Applied methods for quality control comprise standard methods but also non-destructive testing methods that has been or is being developed and adapted to the specific task of quality control of welds and canister components /SKB 2006c, SKB 2006d/.

The methods used in fabrication, welding and non-destructive testing must be qualified, by a documented investigations ensuring that the canisters satisfy the fundamental requirement that the canister is a reliable barrier in the final repository /SKB 2006e/. Specified requirements have to be stipulated for each part of the process and the qualification is then carried out to these requirements.

Handling, transportation and emplacement in deep repository

The canister is designed to be lifted in the lid during encapsulation, transportation, and deposition in the deep repository. Defects may however occur during handling etc. If this is the case, each defect shall be evaluated with respect to the e.g. the following handling safety as well as long-term safety. The canister is in many aspects an assumption for the design of the systems for handling, transportation and emplacement in the deep repository so that they provide the assurance of safety.

4.2 Variables

4.2.1 Overview

The repository sub-system cast iron insert and copper canister is described geometrically by the canister geometry, with respect to radiation by the radiation intensity (mainly γ- and neutron radiation) and thermally by the temperature. Mechanical stresses characterise the sub-system mechanically and material compositions for insert and canister characterise it chemically. The variables are defined in Table 4-1.

4.2.2 Canister geometry

Initial value

A summary of the geometry for both the BWR and PWR versions of the canister are given in Table 4-2 and the geometry of the BWR version is shown in Figure 4-3. The given values are those specified in the technical specifications. This variable also includes the geometries of initial discontinuities in the materials e.g. in the welds and canister components.

Initial copper thickness

Discontinuities under normal operation have been observed in a test series of 20 canister lid welds. Maximum discontinuities sizes are of the order of a few millimetres with the largest being 4.5 mm /SKB 2006d/. Normal operation is defined as conditions where the observable parameters of the sealing process are within a defined "process window". The probability of detecting these discontinuities is not taken into account. This omission is however of minor importance since i) the probability of detection for these discontinuities sizes is fairly low and ii) these discontinuities are acceptable, meaning that a possible detection would not lead to any corrective measures. If the sealing process parameters at any time lie outside the process window, the statistics of discontinuities sizes referred cannot be taken as representative.

A first evaluation of the reliability of the sealing process itself, of its surveillance functions and of the NDT suggests that the likelihood of disturbed operations leading to copper thicknesses below 40 mm is very low. A first crude estimate is that at most one percent of the canisters leaving the encapsulation plant would have such defects. These events will lead to a distribution of copper thicknesses that is difficult to determine. A first, pessimistic assumption is that all such canisters have a minimum copper coverage of 35 mm. This, however, clearly underestimates the performance of the NDT system.

Table 4-1. Variables for cast iron insert and copper canister.

Variable	Definition
Canister geometry	Geometric dimensions for the canister components. This also includes a description of any fabrication defects in welds etc.
Radiation intensity	Intensity of α-, β-, γ- and neutron radiation as a function of time and space in the canister components.
Temperature	Temperature as a function of time and space in the canister components.
Mechanical stresses	Mechanical stress as a function of time and space in the canister components.
Material composition	Material composition of the canister components.

Table 4-2. Geometry of the assembled canister.

Canister	
Length:	4,835 mm
Diameter:	1,050 mm
Total weight (including fuel):	24,600 kg (BWR) 27,000 kg (PWR)
Copper tube	
Wall thickness:	5 cm
Inner length:	457.5 cm
Inner diameter:	95.3 cm
Lid thickness:	5 cm
Bottom thickness:	5 cm
Cast iron insert	
Length:	457.3 cm
Diameter:	94.9 cm
Channels for fuel assemblies	See Figure 4-3
Number:	12 (BWR) 4 (PWR)
Side:	160 mm (BWR) 230 mm (PWR)
Distance between sides:	50 mm (BWR) 150 mm (PWR)

Table 4-3. Weight of the canister components.

	Copper (kg)	**Cast iron (kg)**
Canister for BWR	7,400	13,600
Canister for PWR	7,400	16,400

Thus, 99% of the canisters are assumed to have a thickness between 40 and 50 mm and one percent between 35 and 40 mm in the reference initial state in SR-Can, see further the SR-Can data report /SKB 2006g/. These thicknesses refer only to the seals of the canisters. The distribution is used for both the top and the bottom seals, since these are to be welded and inspected using the same methods.

The major part of the copper shell is assumed to have a thickness of 50 mm in SR-Can. The occurrences of discontinuities in the canister components and the reliability in the manufacturing processes have not been evaluated in detail.

Uncertainties

The evaluations of the occurrences of discontinuities in the canister components and the reliability of the manufacturing methods and NDT of canister components are tasks to be performed.

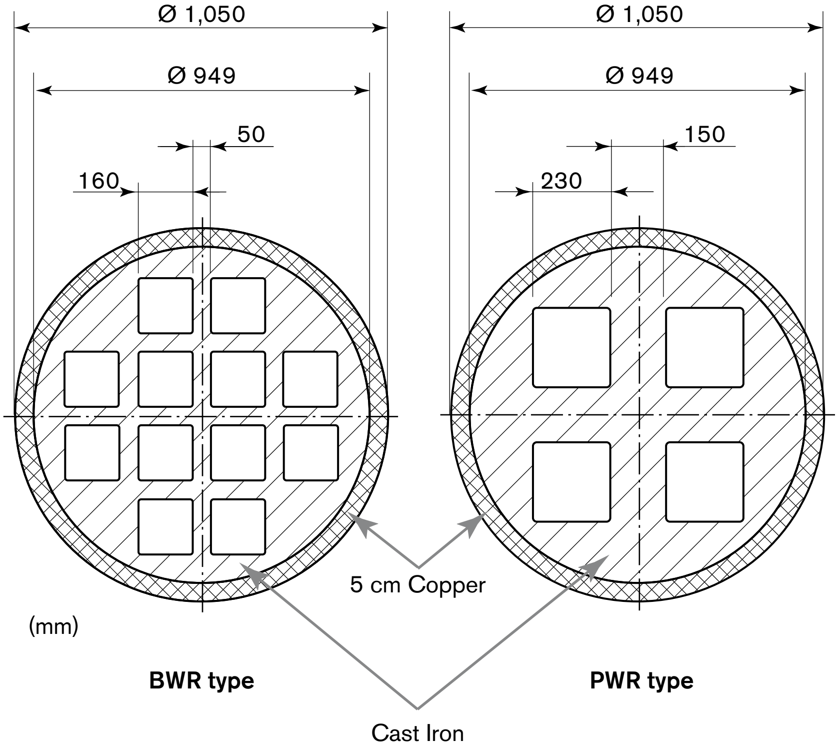


__Figure 4-3.__ Schematic design of insert for 12 BWR or 4 PWR assemblies for a 5 cm thick copper shell.

4.2.3 Radiation intensity

Initial value

The γ-dose rate outside the canister is of importance for radiolytic decomposition of water and for nitric acid formation from entrapped air before saturation of the buffer.

The surface dose on the canister may not exceed 1 Gy/h. The dose rate caused by γ- and neutron radiation outside the canister has been calculated with a model based on a coupled photon and electron transport theory /Lundgren 2004/. The results show that the average dose rate at the canister surface is about 0.15 Gy/h. The dose rate around the canister varies with a factor of about 4 due to the design of the canister insert.

Uncertainties

The calculations performed by /Lundgren 2004/ show, that the influence of the local conditions at the surface is rather small, and that the radiation dose to water outside the copper surface is reasonably well determined by the gamma dose rate.

4.2.4 Temperature

The temperature criterion for the canister and buffer has been changed during the last few years. It has changed from 100°C at the canister surface to max 100°C inside the buffer. The peak temperature criterion for the buffer, set to 100°C in order to avoid mineral transformations, is an example of a criterion with a considerable margin as documented in the Buffer and backfill process report /SKB 2006f/.

Initial value

The surface temperature on the canister is estimated to be around 90°C but is dependent on the handling sequence at deposition (cooling) and the inventory of the fuel assemblies placed in the canister. The decay heat in one canister is limited to 1,700 W, to fulfil set temperature requirements in the deposition hole.

Uncertainties

The main uncertainties come from relatively large uncertainties concerning the heat transfer from the canister surface to the surroundings.

4.2.5 Mechanical stresses

Initial value

Residual stresses remain in the copper lid weld after the canister is sealed. Attempts to determine the size of these stresses have been made both experimentally /Leggatt 1995/ and by means of modelling /Lindgren et al. 1999/. The modelling showed that immediately after welding (20 seconds) the annual tensile stresses in particular may be high, up to 100 MPa, but they gradually relax and have fallen to about 50 MPa after a week. The tensile stresses will then gradually turn into compressive stresses when the copper shell comes into contact with the insert and the process stops after about three years /Lindgren et al. 1999/.

The tensile stresses that remain after a very long time are low and are judged not to be of any importance for canister life.

Uncertainties

The measured and the calculated residual stresses are in relatively good agreement. The greatest residual stresses immediately after welding are estimated to be in the range 50–100 MPa. The effects of cold working are being evaluated.

4.2.6 Material composition

Copper shell

The copper shell is made of pure oxygen-free copper material that shall full fill the specifications in EN 1976:1988 for the grades Cu-OFE (Table 4-4) or Cu-OF1 (Table 4-5) with the following additional requirements: O < 5 ppm, P = 30–70 ppm, H < 0.6 ppm, S < 8 ppm. SKB has compiled technical specifications with requirements on the copper material, KTS 001 for ingots and billets and KTS 002 for manufactured copper components.

Table 4-4. Composition of the copper material, EN 1976 Cu-OFE.

Element	Cu	Ag	As	Fe	S	Sb	Se	Te	Pb
	%	ppm$^{b)}$→							
	99.99$^{a)}$	25	5	10	15	4	3	2	5
		Bi	**Cd**	**Mn**	**Hg**	**Ni**	**O**	**Sn**	**Zn**
		ppm$^{b)}$→							
		1	1	0.5	1	10	5	2	1

$^{a)}$ Including Ag.

$^{b)}$ Maximum content.

Table 4-5. Composition of the copper material, EN133/63 Cu-OF1.

Element	Cu	Ag	As	Fe	S	Sb	Se	Te	Pb
	remaining	ppm→							
		25[b]	5[c]	10[d]	15[b]	4[b]	2[e]	2[f]	5[b]

[a] Including Ag.
[b] Maximum content.
[c] Sum of As+Cd+Cr+Mn+Sb ≤ 15 ppm.
[d] Sum of Co+Fe+Ni+Si+Sn+Zn ≤ 20 ppm.
[e] Sum of Bi+Se+Te ≤ 3 ppm.
[f] Sum of Se+Te ≤ 3.0 ppm.

Cast insert

Cast iron is the name given to iron-carbon alloys with more than approximately 2% carbon by weight. The insert is cast from spheroidal graphite cast iron (SS 14 07 17) and shall fulfil the mechanical properties in EN 1563 grade EN-GJS-400-15U. The steel lids are produced from steel plates and the plate shall be according to EN 10025 S355J2G3, SS 14 21 72 or similar grade. The chemical composition (see Table 4-6) and tensile strength shall meet the requirements defined in the standard. In addition to carbon, the cast iron also always contains silicon, manganese, phosphorous and sulphur. Silicon, manganese and phosphorus can also be used in different concentrations as alloying elements to control the properties of the iron. Other alloying elements such as copper, nickel, and chromium are also commonly used as additives to control the properties and increase the strength.

Profiles for steel section cassettes are either hot or cold formed. The material specifications for profiles forming the steel section cassette (channels for fuel assemblies) coincides with the requirements in EN 10210-1 (hot formed)/EN 10219-1 (cold formed) or SS 14 21 74-03 or SS 14 21 74-04. Plates and flat bars shall full fill the requirements in EN 10025 S235JRG2, SS 14 13 12 (structural steel) or similar. The O-ring sealing the lid is made of polymers (Viton®).

Uncertainties

The uncertainties in materials composition are small for the canister materials. Small variation in the chemical composition of the copper will have negligible consequences for the canister corrosion. Small variations in the chemical composition of the cast insert can affect its mechanical properties but not to the extent that it fails to meet the mechanical strength criterion with sufficient safety margins. Incorrect graphite structure will have a stronger impact on the mechanical strength of the insert.

Table 4-6. Chemical composition (%) of cast iron according to standard.

Element	Insert (cast iron) SS 14 07 17
C	3.2–4.0
Si	1.5–2–8
Mn	0.05–1.0
P	0.08
S	max 0.02
Cr	–
Ni	0–2.0
Cu	–
Mg	0.02–0.08
Ti	
V	
N	
Others	

5 Buffer

5.1 General

The copper canister disposed in the deposition holes will be surrounded by a clay buffer. The buffer is deposited as bentonite blocks and rings. The blocks are placed below and above the canister and the bentonite rings surround the canister. On disposal, slots are left for technical reasons between the canister and buffer and between buffer and rock. The filling material in the upper metre of the deposition hole is part of the sub-system backfill in the deposition tunnel, see Chapter 6.

Two different types of bentonite are considered as reference buffer material for the purpose of SR-Can. One is a natural sodium bentonite from Wyoming (MX-80) supplied by the American Colloid Company and the other is a natural calcium bentonite from Milos (Deponit CA-N) supplied by Silver and Baryte. The two materials analysed in SR-Can are examples of possible options.

The description following reflects SKB's present knowledge based on performed research, development and demonstrations e.g. fabrication of bentonite buffer for the experiments in Äspö HRL, drilling of deposition holes and emplacement of canisters and buffer at Äspö HRL /SKB 2004a/. Future development of excavation methods, machinery and other equipment as well as gathering of design basis data it is found necessary to keep the freedom of choice with regard to methods remain also after the deposition has begun. This means that the final procedures are not definitively developed yet.

Drilling of deposition holes

The drilling of the deposition holes can start when the deposition tunnel is excavated to its full length. The preliminary positions of the deposition holes are determined in connection with rock characterisation of the deposition tunnel. The deposition hole excavation work begins with core drilling of a pilot hole at the intended centre positions for the deposition holes. The core is then examined with the purpose to determine if the rock is suitable. The position of the deposition hole is marked with signs after approval of the drilled rock core sample.

A levelling concrete slab of low alkali cement, approximately 2.5 × 2.5 m, is then cast above the position for each deposition hole. The purpose of this slab is to provide good starting condition for the deposition hole drilling machine and to prevent water from the tunnel to enter the deposition hole. While this work is being done, the floor of the tunnel is levelled with macadam in preparation for heavy loads. The deposition hole is then bored, using full-face boring. The boring equipment is centred over the position of the hole and stabilised by hydraulic devices, which brace against the roof and walls of the tunnel. The drill cuttings are collected in containers using a vacuum unit.

After completion of the boring of all deposition holes in one tunnel the holes are subject for laser scanning and measurement. The measurement will ensure a very good knowledge about the condition and dimensions of each deposition hole. This information is required for determination of the final density of the buffer after saturation.

All holes in the deposition tunnel will be bored before deposition of buffer and canisters can start. A deposition hole has a diameter of 1.75 m and a depth of about 8 m.

Manufacturing of buffer

The important aspect in the manufacturing of bentonite blocks and rings and the deposition process is to get a final density of the water saturated buffer. The density requirement for the saturated buffer is 1,950–2,050 kg/m^3. Based on experience from the field tests in Äspö HRL and the dry density of installed blocks, the densities in the deposition holes have been calculated. The conclusion is that it should be possible to meet the target density for the saturated buffer in the deposition holes.

The bentonite is bought in bulk form and transported by ship to a suitable harbour. The bulk is transported from the harbour to an indoor storage with dry conditions and the temperature kept above 15°C. From here the material is moved to the production facility where the bentonite mill is located.

There are primarily two methods available for fabrication of bentonite blocks and rings; unaxial pressing and isostatic pressing. Objects thicker than 0.5–1 m cannot be easily produced by unaxial pressing and the development of isostatic pressing is therefore put forward.

Fabrication of the blocks and rings by isostatic pressing will require that both the outside of the blocks and rings plus the inside of the rings are machined to the tolerances specified. Also the top and bottom surface has to be machined in order to get the required straightness of the pile of bentonite blocks and rings. This is very important in order to be able to keep small tolerances between the canister and the inside of the buffer rings.

The bentonite blocks will be manufactured to a dry density that gives the target density required for the buffer in the deposition hole. The needed block density is dependent on the empty volume in the slots between the canister/buffer and the buffer/rock.

Quality control

It is important to select a supplier of bentonite that is able to deliver a material with an even quality. Furthermore the supplier must have a well documented quality control system. Each shipping of bentonite will be followed by a protocol from the supplier that describes the actual composition of the material.

The need for bentonite sampling and material tests are not finally worked out but identified at the following occasions: 1) When the material is delivered to the production facility, 2) Before water is added to the bentonite in the mixer, 3) After mixing has been carried out and 4) In connection with the compaction of a block. Item number 1 aims at checking the material characteristics in order to accept the individual delivery (Acceptance tests). Item 2 and 3 aim at dimensioning and checking the water mixing activity (Mixing tests). Item 4 aims at collecting material from a specific block for storage (Material storage) and for characterisation of physical, chemical and mineralogical properties (Characterisation tests).

The details of the testing procedure and the number of test samples per shipping of bentonite are yet to be determined. Today, it is expected that the acceptance testing will use the following techniques: water ratio, free swelling (graduated measuring glass), liquid limit (cone method), grain size distribution, powder XRD combined with Rietveld Method, ICP/AES chemical analyses, and cation exchange capacity analyses.

The combination of tests together with the specifications from the supplier will ensure that all the material that goes into block manufacturing will meet the specifications with respect to montmorillonite content.

Quality control is undertaken also during the manufacturing of the blocks and rings. One important measure to control is the water content before pressing so that this can be adjusted before the bentonite powder isostatically pressed. The dimensions and shapes of the blocks and rings are also controlled.

Emplacement of buffer

The buffer emplacement in a tunnel may take place several months after the deposition holes were drilled. Before the emplacement procedure starts all holes in the actual tunnel are prepared.

The deposition holes are assumed to be filled with water in the meantime, why draining is the first step in the preparation.

Deposition starts with the hole at the far end of the tunnel. The buffer is put into position by a specially designed buffer filling vehicle and the pile of bentonite rings is assumed to have the same height as the canister. The bentonite lining is thereafter checked. The emplacement of the copper canister will be done with a specially designed deposition machine which also places a bentonite block on top immediately after the canister is emplaced. The emplacement of the canister will probably be documented with a photograph of the canister in its final position before the remaining bentonite blocks are emplaced. Finally the remaining bentonite blocks are put in place by the bentonite buffer filling vehicle.

The final handling procedures and the final design of the buffer filling vehicle and the deposition machine are not decided yet but do not affect the description of the work procedure. The small slots between the components in the deposition holes mean a very limited risk for faulty emplacement of the buffer and canister.

The bentonite must be protected from water or high humidity until the tunnel is backfilled. The reason is that the buffer may start swelling before the deposition of the canister and before the tunnel backfill can apply its counterforce on the buffer. This is not allowed to occur, since the density of the buffer might become too low, and that has to be prevented. The wetting of the buffer and uptake of water from the atmosphere in the deposition hole can be prevented by different means. One possible method, which has been tested in the Prototype Repository in Äspö HRL, is to insert a drain tube in the deposition hole and to protect the whole buffer with a plastic bag that is kept sealed until the backfilling of the tunnel starts, see Figure 6-1.

The bag and drain tube is applied before the bottom block and rings are inserted. The plastic bag will be sealed after completion of the installation of the canister and top bentonite blocks. The water level in the slot outside the concrete pad at the bottom of the hole and also the humidity in the plastic bag will be monitored during the waiting period. The bag, pumps, and pipes are removed in sequence as the backfilling of the deposition tunnel progress. The removal of the plastic bag and draining equipment is made in order to avoid such stay materials to be left in the deposition hole. In SR-Can it is assumed that the removal of these items will be successful in all cases, or that effective remedial action will be taken in the event of failure.

5.2 Variables

5.2.1 Overview

The buffer is bounded on the inside by the interface towards the canister, on the outside by the interfaces towards the deposition hole, at the bottom by the interface towards the bottom concrete plate and on the top by the interface towards the backfill.

The buffer as it is delimited by the variable buffer geometry is characterised thermally by its temperature and with respect to radiation by its radiation intensity, mainly γ- and neutron radiation. Hydraulically, the buffer is characterised by its water content, and sometimes by gas concentrations and by hydrovariables (pressure and flows), which are mainly of interest during the phase when the buffer is being saturated with water. The buffer is mechanically characterised by its stress state.

The chemical state of the buffer is defined by its composition including the montmorillonite composition and impurities. The chemical state is also defined by the pore water composition and the occurrence of structural and stray materials in the deposition hole.

The variables are defined in Table 5-1. The values of some of the variables are dependant on the density of the different phases. The following values have been used: density of water (ρ_w) is 1,000 kg/m^3 and density of clay solids (ρ_{cs}) is 2,780 kg/m^3.

Table 5-1. Variables for buffer.

Variable	Definition
Buffer geometry	Geometric dimensions for buffer. A description of e.g. interfaces on the inside towards the canister and on the outside towards the geosphere.
Pore geometry	Pore geometry as a function of time and space in buffer. The porosity, i.e. the fraction of the volume that is not occupied by solid material, is often given.
Radiation intensity	Intensity of (α-, β-,) γ- and neutron radiation as a function of time and space in buffer.
Temperature	Temperature as a function of time and space in buffer.
Water content	Water content as a function of time and space in buffer.
Gas content	Gas contents (including any radionuclides) as a function of time and space in buffer.
Hydrovariables (flows and pressures)	Flows and pressures of water and gas as a function of time and space in buffer.
Stress state	Stress conditions as a function of time and space in buffer.
Bentonite composition	Mineralogical/Chemical composition of the bentonite (including any radionuclides) in time and space in buffer. Levels of impurities in time and space in buffer. Impurities also include minerals, other than montmorillonite.
Montmorillonite composition	Mineralogical composition and structure of the montmorillonite mineral in the bentonite. This variable also includes the charge compensating cations attached to the montmorillonite surface.
Pore water composition	Composition of the pore water (including any radionuclides and dissolved gases) in time and space in buffer.
Structural and stray materials	Chemical composition and quantity of structural and stray materials.

5.2.2 Buffer geometry

Initial values

The buffer sub-system initially consists of highly compacted bentonite blocks and rings emplaced around the canister in the deposition hole. It also includes the slots between the bentonite and the rock surface and canister surface respectively. The initial geometry is determined by the dimensions of the canister and the buffer thickness required obtaining the expected function.

The dimensions of the canister are given in Section 4.2.2, and the dimensions of the rings and blocks are given in Table 5-2. The blocks and rings are assumed to have a maximum height of 500 mm, since higher blocks and rings cannot be produced today, see Figure 5-1. The aim is to develop the fabrication so that higher blocks and rings can be made in the future. One bentonite block is placed below the canister, ten rings surround it and three blocks are placed above the canister, see Figure 5-2. The buffer thickness on top of the canister is about 1.5 m. The geometry of the blocks and rings described here is similar to the geometry used in the Prototype Repository /Johannesson et al. 2004/ and other tests in Äspö HRL where the canister stands on the bottom lid and the axial skirt of the canister of 10 cm penetrates the bottom block by a clearance in the block. The present aim is to have slots between the canister and buffer and between the buffer and the rock of 5 and 30 mm respectively. The bentonite ring on top of the canister can be complemented with small bentonite bricks. Another option is to use a block and make a clearance in it to fit the canister lid geometry.

Thereafter three blocks are placed in the deposition hole. The upper part of the deposition hole is filled with backfill material. The final buffer geometry after saturation is shown in Figure 5-3.

Table 5-2. Geometry and number of bentonite blocks and rings in one deposition hole.

Bentonite blocks and rings	Number of blocks/rings	Diameter (outer), mm	Diameter (inner), mm	Height, mm
Below canister (block)	1	1,690	–	500
Around canister (rings)	10	1,690	1,060	500
Above canister (blocks)	3	1,690	–	500

Total volume of bentonite blocks and rings in one deposition hole is 11.5 m^3 corresponding to a weight of about 22 tonnes. The total volume of bentonite buffer in the repository (6,000 canisters) is 69,000 m^3, with a weight of 132,000 tonnes.

The height of the deposition tunnel can be decreased if the deposition hole has a wedge, which facilitates the deposition of the canister. This is an option, which has not been considered in SR-Can.

Figure 5-1. *Control measurement of bentonite ring.*

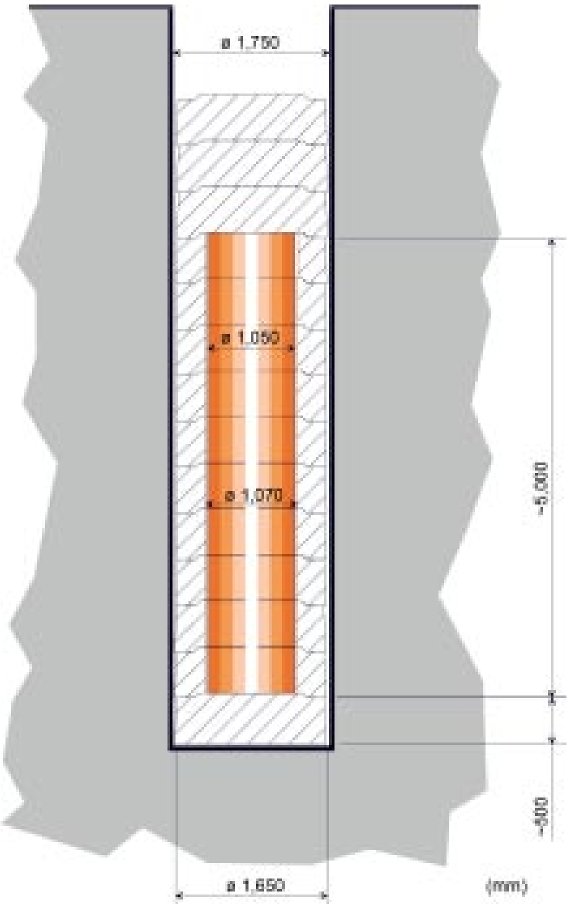


Figure 5-2. *Geometry of bentonite blocks and rings in a deposition hole.*

Rock surface

The radial boundary of the saturated buffer is limited by the rock surface and thus regulated by the demands of the drilling of the deposition holes. The following dimensions and demands are settled on the deposition hole (see Figure 5-3):

- Diameter: 1,750 mm.
- Depth: ~ 8,000 mm.
- Shape: ~ 0.00125 (Δd/l).
- Discrepancy in vertical line at the bottom of the hole: < 16 mm.

Uncertainties

The dimensions (and densities) of the blocks are determined to yield a density after saturation and homogenisation of 1,950–2,050 kg/m^3. The dimensions of the blocks and rings, e.g. the height may very well be increased in the future if higher blocks can be manufactured.

Further, if a deposition hole does not meet the specification this could be handled in different ways. If the hole has too big diameter, the diameter of the blocks and rings could be adjusted to achieve the required final density. It would also be possible to add pellets of bentonite in the slot between the rock surface and the pile of bentonite. This is an option foreseen to be used in e.g. Forsmark where the risk to get spalling in the deposition holes is high due to the rock stress situation at the site. To facilitate the filling of pellets the slot may have to be increased from 30 mm to 50 mm. This is done by a corresponding decrease of the diameter of the bentonite blocks and rings. The optional design has to be developed in detail to ensure the buffer quality and function.

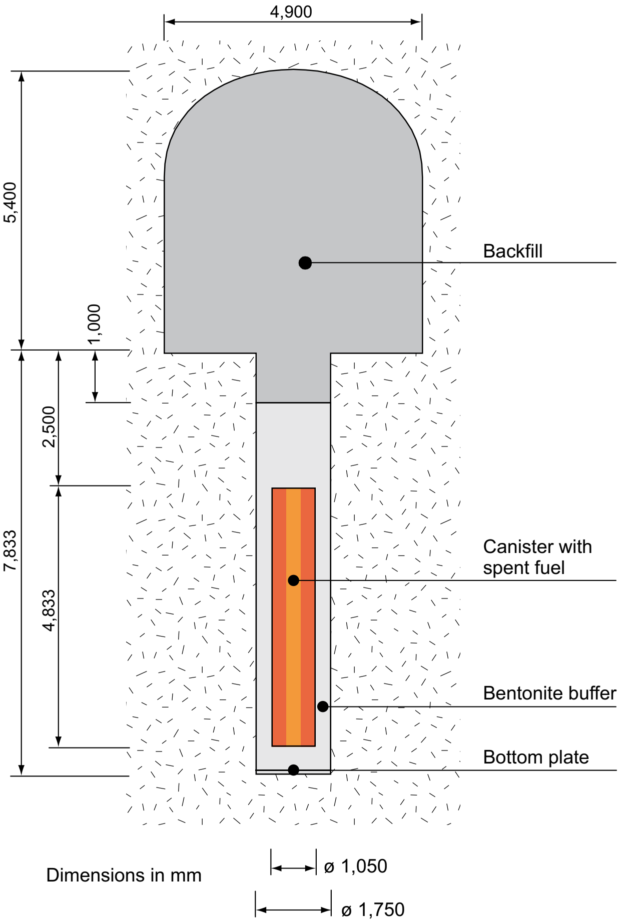


Figure 5-3. *Deposition hole with bentonite buffer and canister.*

5.2.3 Pore geometry

Initial values

The void ratio (e) is given by the ratio of the pore volume and the volume of the solid components /Pusch 2002/. If the water content is zero, i.e. the material is completely dry, the void ratio is given by the dry density and the density of clay solids:

$$\rho_{dry} = \frac{1}{1+e}\rho_{cs}$$

The porosity (ε) is the ratio of the pore volume and total volume of the sample /Pusch 2002/. The porosity is related to the void ratio as following:

$$\varepsilon = \frac{e}{1+e}$$

For the initial rings and blocks, the void ratios and porosities are expected to be:

Blocks: e = 0.680, ε = 0.405

Rings: e = 0.585, ε = 0.369

When manufacturing the blocks and rings, the achieved void ratio and porosity are dependent on the water content of the bentonite and compaction pressure applied.

Uncertainties

The variation in void ratio (Δe) between different blocks and rings is dependent on the variation in water content in the bentonite since the compaction pressure is the same for all blocks and rings. The variation in water content of ± 0.5% yields the following estimated variation in void ratio:

Blocks: $\Delta e = \pm 0.015$

Rings: $\Delta e = \pm 0.015$

There is also an internal variation in the blocks mainly due to variation in water content and due to friction against the walls of the mould during compaction. This variation is also estimated to be about $\Delta e = \pm 0.015$

5.2.4 Radiation intensity

Initial value

/Lundgren 1997/ calculates the initial dose rate on the canister surface and on the outside of the buffer. The γ-dose rate at the canister surface is 100–500 mGy/h (see Section 4.2.3). The dose rate on the outside of the buffer is approximately 2 mGy/h.

Uncertainties

The dose rate on the outside of the buffer has diminished by a factor of about 200, as compared to at the canister surface, and varies in a similar manner as on the inside, see Section 4.2.3.

5.2.5 Temperature

Initial values

The buffer will be in thermal equilibrium with the host rock in the initial state. That value varies with repository site and disposal depth and is approximately 10–15°C. The thermal interaction between the heat-generating canister and the buffer that will take place during deposition counts as a post-closure process, even if some of that interaction will have taken place before actual closure.

Uncertainties

The block storage conditions, the thermal interaction between buffer blocks and the deposition equipment, and the thermal disturbance of the near-field rock caused by the moving tunnel air will have an influence on the actual buffer temperature. The uncertainty may be around 5°. This is of no importance to the thermal evolution in the repository.

5.2.6 Water content

Initial values

The water content (w) is the weight of water divided to the weight of dry material. The bentonite blocks and rings will have an initial water content of 17%. Since the initial dry density (ρ_d) is different for the rings and the blocks (due to different degrees of compaction) the degree of water saturation (S_r), which is the fraction of water filled porosity, will be different.

Blocks: ρ_d = 1,655 kg/m^3, S_r = 70%

Rings: ρ_d = 1,754 kg/m^3, S_r = 81%

Slots: All slots are filled with air from start (no artificial water filling).

Uncertainties

The initial water content in the blocks and rings may vary by ± 0.5%. This is ensured by wrapping the blocks in e.g. plastic foil and storing them under a controlled relative humidity.

The bentonite must be protected from water or high humidity until the tunnel is backfilled, see Section 5.1.

5.2.7 Gas content

Initial values

The unsaturated pores will initially be filled with air, which means 30% of the pore space of the blocks (gas content = 12% of the total volume) and 19% of the pore space of the rings (gas content = 7% of the total volume). 100% of the slots will be air filled.

Uncertainties

Uncertainties in gas content are related to uncertainties in water content. A variation in gas content of ± 0.8% is expected.

5.2.8 Hydrovariables (flows and pressures)

Initial values

The hydrovariables are water and gas flow, and water and gas pressure. Initially there is no flow.

The initial water pressure in the bentonite blocks and rings give rise to very high suction (negative pressure) corresponding to the relative humidity (RH) of the air in equilibrium with the bentonite. At the water content 17% the water pressure (u) in the bentonite is about –40 MPa.

The relative humidity of the air in the slots is assumed to be the same as in the buffer, which has a relative humidity of ~ 75%. This means that there will be no water transport (drying or wetting) from the buffer to the slots. The air pressure corresponds to atmospheric pressure.

Uncertainties

The uncertainty of the water content will be reflected in corresponding uncertainty in suction. The variation in water content (Δw) ± 0.5% yields a variation in relative humidity (RH) of about ± 1%, which in turn yields a variation in water pressure (Δu) of about ± 1,800 kPa.

The air in the tunnel may be more or less humid than 75% relative humidity, which may cause different initial relative humidities of the air in the slots. The influence of such deviation on the behaviour after deposition is though to be insignificant. It is however very important that the blocks are not exposed to a different relative humidity than 75% for a long time before deposition.

5.2.9 Stress state

Initial values

There is initially no external swelling pressure of the blocks and rings but since the pore water pressure is negative there is an internal stress that holds them together. This stress may be expressed as “effective stress” σ' and is defined as $\sigma' = -u \cdot S_r$, which yields

Blocks: $\sigma' = 28$ MPa

Rings: $\sigma' = 32.4$ MPa

In addition there is a vertical stress from the weight of the overburden buffer and backfill. These stresses are small compared to the internal stresses.

Uncertainties

The stresses in the blocks and rings may be inhomogeneous and include shear stresses due to the uniaxial compaction technique. Such inhomogeneities are however not significant for the function of the buffer.

5.2.10 Bentonite composition

Initial values

The composition of the of the buffer materials is described in /Karnland et al. 2006/.

MX-80 bentonite

The mean composition of the examined MX-80 bentonite brand is given in Table 5-3. In addition, grains of pyrite (FeS_2), calcite ($CaCO_3$), siderite ($FeCO_3$), barite ($BaSO_4$) and iron hydroxides in mean individual quantities of less than 1%, may be found.

Deponit CA-N bentonite

The mean composition of the examined Deponit CA-N bentonite is given in Table 5-3. The important difference compared to the MX-80 bentonite is the relatively large content of calcite, which is typical for the Milos bentonites.

Uncertainties

The MX-80 bentonite brand is a blend of several natural bentonite layers and the composition is controlled by the producer. A number of consignments have been examined over the last 20 years and the montmorillonite content has not varied more than a few percent. The impurities

Table 5-3. Bentonite composition of MX-80 and Deponit CA-N. The uncertainties are mainly related to the precision of the analysis method used.

Component	MX-80 (wt-%)	Deponit CA-N (wt-%)	Uncertainty (± wt-%)
Calcite + Siderite	0–1	10	1
Quartz	3	1	0.5
Cristobalite	2	1	0.5
Pyrite	0.07	0.5	0.05
Mica	4	0	1
Gypsum	0.7	1.8 (anhydrite)	0.2
Albite	3	0	1
Dolomite	0	3	1
Montmorillonite	87	81	3
Na-	*72%*	*24%*	*5*
Ca-	*18%*	*46%*	*5*
Mg-	*8%*	*29%*	*5*
K-	*2%*	*2%*	*1*
Anorthoclase	0	2	1
Organic carbon	0.2	0.2	–
CEC (meq/100 g)	75	70	2

may vary slightly, but generally feldspars, quartz and cristobalite dominate, and other impurities are seldom found in quantities over 1%.

The Deponit CA-N bentonite composition may be controlled by the producer since there is a minor variation in the pit. Only one consignment has been examined but the composition of a commercial product from Milos can be expected to be relatively constant according to other studies. Feldspar may be present up to a few percent in addition to the above minerals. It is likely possible to determine the composition with a minimum and/or a maximum value for all main minerals with only small deviations from the given values.

5.2.11 Montmorillonite composition

Initial values

MX-80 bentonite /Karnland et al. 2006/

The cation exchange capacity (CEC) is 0.75 eq/kg for the total MX-80 material, and 0.85 eq/kg for the clay fraction. The molar weight of the montmorillonite based on an $O_{20}(OH)_4$ cell is 750 g and the layer charge is –0.63. The structural formula of the montmorillonite component in the original MX-80 material is:

$(Si_{7.86}\,Al_{0.14})\,(Al_{3.11}\,Fe^{3+}_{0.37}\,Mg_{0.50}Ti_{0.01})\,O_{20}\,(OH)_4,\,Na_{0.47}\,Ca_{0.05}\,Mg_{0.02}\,K_{0.01}$

Deponit CA-N /Karnland et al. 2006/

The CEC is 0.70 eq/kg for the total Deponit CA-N material, and 0.85 eq/kg for the clay fraction. The molar weight based on an $O_{20}(OH)_4$ cell of the montmorillonite is 751 g and the layer charge is –0.76. The structural formula of the montmorillonite component in the Deponit CA-N material is:

$(Si_{7.74}\,Al_{0.26})\,(Al_{2.90}\,Fe^{3+}_{0.44}\,Mg_{0.58}Ti_{0.08})\,O_{20}\,(OH)_4,\,Na_{0.18}\,Ca_{0.17}\,Mg_{0.11}\,K_{0.02}$

Uncertainties

It is possible to repeatedly determine CEC within a few equivalent units for a bentonite material, by use of standardized methods and after ion exchange to a monovalent ion. However, different methods may result in rather large discrepancies. The composition of original charge compensating cations is further difficult to quantify since all methods to some extent may lead to internal ion exchange. The structural formulas can be expected to be quite accurate, except for the distribution of the charge compensating cations. The maximum error for the latter is estimated to be 20% of given values.

5.2.12 Pore water composition

Pore water composition in bentonite has been discussed and described in many reports, articles and previous safety reports, see for example /Bradbury and Baeyens 2002/. In general, the pore water composition is mainly determined by:

- The charge compensating cations in the montmorillonite.
- Equilibrium with the minerals in the bentonite.
- Ions added with solution.
- The total amount of water.

The charge compensating cations give a high cation concentration between the montmorillonite mineral flakes. The minerals in the system lead to equilibrium concentrations for all possible ions with the available amount of water. This equilibrium may lead to quite different local conditions. At short distances between the montmorillonite flakes, the conditions will be dominated by the charge compensating cations, and at large separations between the montmorillonite flakes the conditions will be dominated by the involved minerals. The concentration of a specific ion may thereby have a spatial variability of several orders of magnitude.

Addition of water to the system will decrease the concentration of charge compensating cations. The equilibrium concentration with involved minerals will still be the same in volumes unaffected by the charge compensating cations if the minerals are not completely dissolved, and the equilibrium concentration will actually increase in volumes governed by the charge compensation cations.

The initial pore water composition may be calculated but not directly measured. A water solution may e.g. be squeezed from the bentonite, which leads to a composition unique for the applied equilibrium condition, but not for the initial conditions.

In the initial unsaturated bentonite, the water is mainly situated between the montmorillonite surfaces, and strongly dominated by the charge compensating cations. The calculated initial concentrations cannot be used for extrapolation to conditions with other amounts of water, but the new concentrations may be calculated taking into account the equilibrium conditions.

Uncertainties

The ion equilibrium between charge compensating ions and all other ions in the system is not fully understood.

5.2.13 Structural and stray materials

Initial values

No quantities of structural materials are assumed to be left in the deposition holes. It should be noted that the concrete bottom plate is a sub-system of its own, see Chapter 6.

Potential stray materials in the deposition holes are lubrication oil (hydrocarbons) from the boring of the deposition holes and human waste e.g. urine (carbonhydrate). The major part of the oil will be removed together with the cuttings. The deposition holes are assumed to be filled with groundwater in the meantime between drilling and emplacement. Draining is therefore the first step. This means that water soluble stray materials are expected to be pumped out. In addition the deposition holes will be carefully controlled and cleaned prior to the emplacement of the buffer and canister. To limit the amount of oil left in the holes one option is to use degradable hydraulic oils and lubrication greases. Most of these oils are based on biological oils and alcohols from the mineral oils.

Uncertainties

The information referred to is relatively uncertain and the estimates of the amounts will be more detailed as the design of the repository progress. An update of the inventory of potential stray materials in the repository has been done (published as an internal SKB report) during spring 2005. From this study it was concluded that no stray materials are expected to be left in the deposition holes and that the routines and method for the cleaning the deposition holes, which has not yet been finally developed, will be designed to minimise the amounts.

The spillage of lubrication oil from the TBM used for drilling of deposition holes in Äspö HRL was maximised to 10 litres per hole. It is however believed that the major part of this amount is distributed in the cuttings which are removed by a vacuum pump.

The amount of oil spillage on the bentonite blocks from the fabrication is very small. This is based on the SKB's experiences from fabrication of blocks and rings e.g. for the experiments in Äspö HRL.

6 Bottom plate in deposition holes

6.1 General

The bottom in the deposition hole can not serve as ground for the buffer as the present technique for excavation of the deposition hole does not give a flat and horizontal surface. The bottom of the deposition holes have, therefore, to be levelled off with a bottom plate. The bottom plate serves as a rigid support for the bentonite blocks and the canister. The pile of bentonite blocks thereby gets a vertical centre line defined, so that the canister can enter gently and the gap between blocks and rock surface is even enough to allow the block lifting tools and the other parts to pass freely.

The final design of the bottom plate has not yet been decided and development of different solutions is in progress. For the purpose of SR-Can it is foreseen that the bottom plate will be cast of concrete containing low pH cement. Bottom plates fabricated with this technique with the same layout has been used in the full scale Prototype Repository Experiment in Äspö HRL /Johannesson et al. 2004/. The development of suitable low alkali cement is in progress and the receipt given here is one possible example. However, the development and testing of different recipes are ongoing and the final decision has not been taken. A copper plate is placed on the concrete surface to protect the bentonite from being wetted with ground water, which can penetrate the concrete plate. A periphery slot is left between the concrete bottom plate and the rock wall. Here the ground water can be collected and pumped up from the hole, see Figure 6-1. The drain pipe is connected to a vacuum pump or similar equipment at the tunnel floor. Different type of evacuation systems could be used.

Casting of bottom plate

The bottom plate is cast in a mould mounted to the deposition hole wall at a given position. A copper net is mounted in the bottom of the mould to create a waterway and to prevent flow of ballast. The bottom plate is cast in two steps: first step is a coarse casting to create a slot between the deposition hole wall and the plate where water can pass and be pumped out, and second step is a fine casting to create the horizontal and flat surface. The mould is removed carefully.

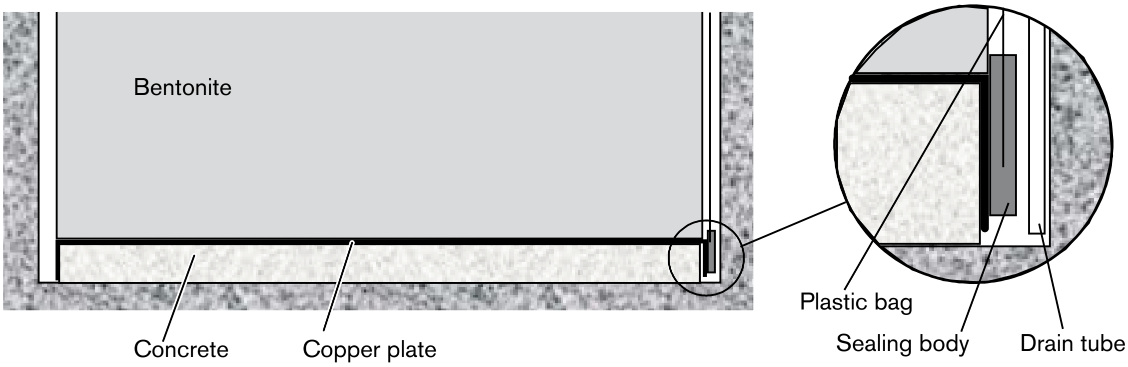


Figure 6-1. Bottom plate in deposition hole.

6.2 Variables

6.2.1 Overview

The bottom plate is bounded on the bottom by the interface towards the rock and on the top by the interface towards the bentonite buffer. A periphery slot is left between the concrete bottom plate and the rock wall.

The bottom plate as it is delimited by the variable bottom geometry in the hole is characterised thermally by its temperature, hydraulically by the hydrovariables (pressure and flows), and mechanically by the stress state. The chemical state of the bottom plate is defined by its material composition and pore water composition.

The variables are defined in Table 6-1. The dose rate in the bottom plate has not been calculated, since it is as low as on the outside of the buffer and is judged to be of no importance for the safety assessment.

6.2.2 Bottom plate geometry (and pore geometry)

The purpose of the bottom plate is to serve as an even base for the bentonite blocks. It is very important that the bottom plate is horizontal. The bottom plate may have a deviation in the horizontal plane between the opposite sides of 1 mm.

The final layout of the bottom plate is not defined and consequently one example of a cast bottom plate is given here. The thickness of the bottom plate will be adapted to the roughness of the rock and will be about 5 cm at the thinnest part and 10 cm as a maximum. A periphery slot, approximately 30 mm wide, is left between the concrete bottom plate and the rock wall, to support drainage. The volume of the concrete bottom plate is estimated at about 0.2 m^3 (diameter 1.65, thickness 0.1 m). The copper plate on top is a few millimetres thick and the cupper net, inserted during casting, is about 1×1 m with a mesh size of 0.15 mm.

The void ratio (e) in the concrete bottom plate is estimated to be ~ 0.02.

Table 6-1. Variables for bottom plate in deposition hole.

Variable	Definition
Bottom plate geometry (and pore geometry)	Geometric dimensions of concrete bottom plate in deposition hole. A description of e.g. interfaces towards buffer in deposition holes and towards the geosphere.
	Pore geometry as a function of time and space in concrete bottom plate. The porosity, i.e. the fraction of the volume that is not occupied by solid material is often given.
Temperature	Temperature as a function of time and space in concrete bottom plate in deposition holes.
Hydrovariables (pressures and flows)	Flows and pressures of water and gas as a function of time and space in concrete bottom plate in deposition holes.
Stress state	Stress state as a function of time and space in concrete bottom plate in deposition holes.
Materials – composition and content	Chemical composition and content of the materials in concrete bottom plates (including any radionuclides) in time and space. This variable also includes material sorbed to the surface.
Pore water composition and content	Composition (including any radionuclides and dissolved gases) of the pore water and pore water content in time and space in concrete bottom plate.

Uncertainties

Uncertainties of relevance for the initial state and the development of the repository are small. It is however very important that the bottom plate is flat and horizontal, which is checked prior to the deposition of the buffer.

6.2.3 Temperature

Initial values

The concrete bottom plate in the deposition hole will be in thermal equilibrium with the undisturbed host rock in the initial state. That value varies with repository site and disposal depth and is approximately 10–15°C. The heat evolution during the curing of the concrete is judged to be of no importance after deposition of the canister and the bentonite. The thermal interaction between the heat-generating canister and the buffer and the bottom slab that will take place during deposition counts as a post-closure process, even if some of that interaction will have taken place before actual closure.

Uncertainties

The uncertainty may be similar to that of the buffer i.e. around 5°. The initial temperature of the bottom plate is of no importance to the thermal evolution in the repository.

6.2.4 Hydrovariables (pressure and flows)

The hydrovariables are water and gas flow and water and gas pressure. Initially there is no flow.

Initial value

Initially there will be no water in the bottom slab since the water is consumed during the curing of the concrete. However, the rock will supply the concrete with water and the pores are at start assumed to be filled with water, which corresponds to a few percent of water content. The water pressure in the bottom plat will be zero since it is assumed to be water saturated.

Gas content: There will be very small amounts of air in the bottom plate.

Uncertainties

The water content of the concrete bottom plate is uncertain.

The water pressure in the concrete bottom plate may be higher if there is a fracture with high pressure connected to the plate.

6.2.5 Stress state

Initial value

Not relevant for the initial state.

6.2.6 Materials – composition and content

Initial value

The bottom plate will be made of low alkali concrete. The development of a recipe for the low alkali cement is in progress and an example of a receipt is given in Table 6-2. The concrete in the surface layer of the bottom plate must flatter out to be horizontal.

The copper plate and the copper mesh are made of a very similar material as the canister, see Section 4.2.6.

Table 6-2. Recipes – low alkali grout for constructions in the repository reported at low-pH workshop in Madrid, Spain, 15–16 June 2005 /Cau dit Coumes et al. 2005/.

Component	Amout (kg)	Comment
Water	160	
Cement	240	Ordinary Portland Cement
Silica Fume	160	Consists primarily of amorphous (non-crystalline silicon dioxide, SiO_2)
SP 40	6	Super plastiziser Density: 1,260 kg/m^3
Ballast (sand)	710	Sand
Ballast	1,160	4–15 mm
Density (kg/m^3)	2,436	

Table 6-3. Chemical composition of low alkali grout components /Möller et al. 1982/.

Product name	Type	CaO wt% (dry)→	SiO_2	Al_2O_2	Fe_2O_3	SO_3	Na_2O	Others
Cement	Ordinary Portland Cement	64–67	20–25	3–7	2–4			

Table 6-4. Estimated amount of the concrete components in one bottom plate.

Component	Amount per deposition hole (kg/m^3)[1)]
Cement	50
Silica Fume	34
SP 40	1.3

[1)] the volume of the concrete bottom plate is estimated at about 0.2 m^3.

6.2.7 Pore water composition and content

Initial value

The pore water composition and content has presently not been specified, since the final design and concrete composition is not specified.

7 Backfill of deposition tunnel

7.1 General

When all deposition holes in a deposition tunnel have been filled with canisters and buffer, the tunnel will be backfilled. Before the backfilling of the tunnel starts, all installations will be removes, as well as concrete and gravel on the floor of the tunnel.

Design during step D1 has as an objective to ensure that the size of the site is large enough, considering all uncertainties related to the rock and its properties, as well as the uncertainties in the Swedish nuclear power program. The repository layout presented here has 6,000 available canister positions and all numbers and values related to the excavated tunnels are given for this layout.

At this stage, the design work generally regards excavation methods, rock grouting and rock support. Detailed design of these construction activities will take place in later design steps /SKB 2004b/.

Excavation of the deposition tunnel

The final decision on excavation technique for the deposition tunnels has not been taken but for the purpose of the SR-Can safety assessment, excavation by drill and blast is analysed. The selected technique – drill and blast – will be done carefully in order to minimize the damage of the rock at the tunnel surface. Suitable drill patterns and explosives have been studied and the tunnel excavation will be based on present and future experiences.

The damages of the tunnel rock surface can be further reduced by excavation of a pilot tunnel and in a second step excavate to the final dimensions. However, normally only the floor of the tunnel would need excavation in two steps, first a gallery and then a bench. The methods for excavation and determination of transmissivity of the excavated disturbed zone (EDZ) need to be studied more in detail prior to the selection of the excavation technique.

The excavation technique will have implications on the dimensions and shape of the deposition tunnel. The excavated tunnel will be controlled by laser scanning (digital measurement) for characterisation of the deposition tunnel and to determine the fracture systems. This will give the actual dimensions of the tunnel and the deviation from the theoretical values. This information would later on be used for determining the amount of backfill material that has to be used for the backfilling of the tunnel.

Backfill concepts

The tunnels will be backfilled and two examples of how this can be accomplished are given. Both examples of the backfilling technique involve placing pre-compacted blocks and pellets in the tunnel.

The aim here is to present backfill concepts that can be developed to fulfil the requirements on, for example, hydraulic conductivity and mechanical properties. It should be stressed that neither the backfill material nor the backfill method have been finally chosen.

The two backfill concepts that are analysed in SR-Can are:

- Blocks of crushed rock and bentonite. The tunnels are backfilled with pre-compacted blocks made out of a mixture of 70 wt-% crushed rock and 30 wt-% bentonite. In addition bentonite pellets are used to fill the gap between the blocks and tunnel surface. The bentonite is of the same type as the buffer.

- Blocks of Friedland clay. The tunnel is backfilled with pre-compacted blocks of Friedland clay. In addition pellets of the same material are used to fill the gap between the blocks and tunnel surface.

The estimation of how much of the cross section that can be filled with blocks and how much can be filled with pellets has been made based on the conceptual design of the emplacement equipment. The size and shape of the blocks for placement in the tunnel has not been determined yet, but in the ongoing investigations parallelpiped blocks with an approximate volume of 0.25 m^3 have been considered.

The upper section (approximately 1 m) of the deposition holes will be filled with the same backfill material as the tunnel. The material will be in situ compacted in both concepts. An option would be to use pre-compacted blocks. In addition, any full-scale rejected deposition hole will be backfilled with crushed rock.

Manufacturing and control procedures

Pre-compacted blocks and pellets

Manufacturing and control procedures are here exemplified in a description valid for blocks made of a backfill mixture of crushed rock and bentonite.

The bentonite, which is bought in bulk, is transported from the harbour to a frost free indoor storage facility, from where it in a later stage is conveyed to the production facility with a bentonite mill. After milling and sieving, the bentonite is blown to silos, which are equipped with a fluidisation devise that facilitates the discharging from the silo.

Mixing of crushed rock and bentonite is made batch-wise using mixing equipment. Moister measurement of the bentonite will be made and from these data, the control system estimates the necessary amount of water that needs to be added from the actual water ratio of the mixture and the desired water ratio. The dosing and weighing of bentonite are made by a cell feeder and a band conveyor. Dosing of ballast is made by vibro-pipes. Adding of water is made by a reciprocal water scale.

The quality control can be made in four steps:

- The clay and the ballast are sampled and analysed. For the clay material the same type of analyses as proposed for the buffer material is made and the results are compared to predetermined limit values. Simpler tests are made for the crushed rock. These may consist of determination of pollutants and determination of the grain size distribution curve.
- After the mixing the composition is controlled. During pre-tests and start-up of the mixing procedure, comprehensive testing of the homogeneity of the mixture in terms of bentonite and water ratio distribution is made and compared to the recipe that is delivered from the mixing plant. While the production mixing is running, a small number of tests determining the bentonite distribution is made while the water ratio, that is easy to measure, and the mixing recipes are used for the continuous monitoring of the homogeneity of the mixture.
- The blocks are tested:
  - Mechanical properties are compared to specifications.
  - The dry density of the blocks is measured and compared to limit values.
- The number and weight of blocks and weight of pellets placed in the tunnel per volume are determined and the total dry density is calculated and compared to specifications. Samples will also be taken after emplacement in the tunnel to ensure that the homogenity is good.

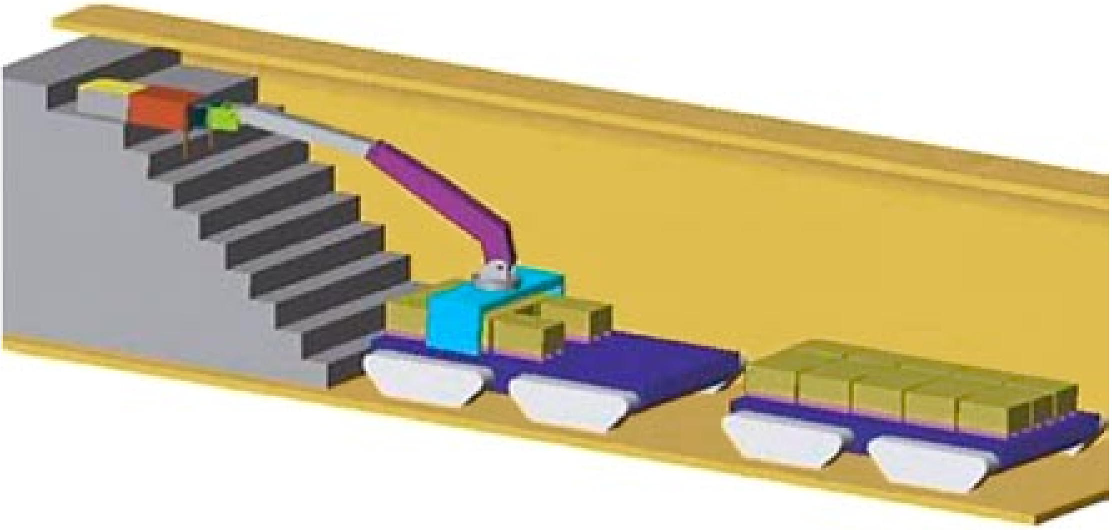


Figure 7-1. *Schematic illustration showing two units for placement of pre-compacted blocks in the tunnel, one for transport and one for placemen.*

7.2 Variables

7.2.1 Overview

The deposition tunnel is constrained in space by the rock surrounding the tunnel, but also by the buffer in the deposition holes and the plugs at the tunnel ends. In the case of rejected deposition holes the sub-system is constrained also by the rock around rejected deposition holes.

The backfill in the deposition tunnel is delimited by the variable backfill geometry. Thermally the backfill is characterised by its temperature. Hydraulically it is characterised by its pore geometry, water content, gas content, and the hydrovariables (pressure and flow). Mechanically, the backfill is characterised by the stress state. The chemical state of the backfill is defined by the material composition. The chemical state is also defined by the pore water composition and the occurrence of structural and stray materials in the deposition hole.

The radiation intensity (dose rate) in the backfill has not been calculated, since it is considerably lower than on the outside of the buffer and is of no importance in the safety assessment.

All variables are defined in Table 7-1. The values of some of the variables are dependant on the density of the different phases and on the bulk density of the system. The assumed density of the blocks are based on laboratory and industrial scale testing of block pressing. The bulk density of pellets are based on the use of bentonite pellets (MX-80) in different tests in Äspö HRL, see for example the description of the installation of the prototype repository by /Johannesson et al. 2004/. The estimation of the average density is based on an assumption on how much of the cross-section can be backfilled with blocks, with pellets, and how much will initially be void. This is based on a study on the technique and equipment for backfilling with blocks and pellets. The actual backfilling has not yet been tested and reported at the writing of this report. It is also assumed that the system will be homogenised with respect to the effective bentonite density in the system during saturation, due to the swelling pressure. This will be further investigated in laboratory tests.

All variables are defined in Table 7-1. The values of some of the variables depend on the density of the different phases. The following values have been used: density of water (ρ_w) is 1,000 kg/m^3, density of clay solids (ρ_{cs}) is 2,780 kg/m^3, and density of crushed rock solids (ρ_{rs}) is 2,650 kg/m^3.

Table 7-1. Variables for backfill of deposition tunnel.

Variable	Definition
Backfill geometry	Geometric dimensions for backfill in deposition tunnel. A description of e.g. interfaces towards buffer and towards the geosphere.
Backfill pore geometry	Pore geometry as a function of time and space in backfill in deposition tunnel. The porosity, i.e. the fraction of the volume that is not occupied by solid material is often given.
Temperature	Temperature as a function of time and space in backfill in deposition tunnel.
Water content	Water content as a function of time and space in backfill in deposition tunnel.
Gas content	Gas contents (including any radionuclides) as a function of time and space in backfill in deposition tunnel.
Hydrovariables (pressure and flows)	Flows and pressures of water and gas as a function of time and space in backfill in deposition tunnel.
Stress state	Stress state as a function of time and space in backfill in deposition tunnel.
Backfill materials – composition and content	Chemical composition and content of the backfill in deposition tunnel (including any radionuclides) in time and space. This variable also includes material sorbed to the surface.
Backfill pore water composition	Composition of the pore water (including any radionuclides and dissolved gases) in time and space in backfill in deposition tunnel.
Structural and stray materials	Chemical composition and quantity of structural materials (rock bolts, filling material in boreholes for grouting, nets, etc) and stray materials in deposition tunnels.

7.2.2 Backfill geometry

Initial values

The geometry of the backfill is very much dependent on the geometry of the excavated tunnels, which on the other hand is dependent on the selected deposition machine and excavation technique, and on the voids missed at backfilling. The final decision about which excavation technique to use has not yet been taken. In SR-Can drill and blast is selected as reference method. The cross section in a drill and blast deposition tunnel is a square with an arched roof. The deposition tunnel is 4.9 m wide and 5.4 m high. These dimensions are the minimum dimensions required. Obviously, it is not possible to excavate to exactly these dimensions and therefore, in calculations of the excavated volume it can be assumed that these dimensions are oversize by approximately 0.2 m or 2.5 m^2.

The layout with deposition areas is site specific. The layouts for Forsmark and Laxemar are shown in Figure 7-2 and Figure 7-3, respectively. The corresponding dimensions and estimated excavated volumes are given in Table 7-2 and Table 7-3. The length of the deposition tunnels is dependent on the distance between the deposition holes, which is determined by the heat transport capacity in the rock. The distance between the deposition holes in Forsmark is 6 m and the distance in Laxemar is either 7.2 m (deposition areas DA27 and DA26) or 7.4 m (deposition areas DA26 and DA27).

The backfill material fills the entire tunnel and the upper section (approximately one metre) of the deposition holes and the limits are thus the rock and the top surface of the upper bentonite block.

Before drilling a deposition hole, a small-diameter borehole is core drilled at its centre and the core is investigated. Normally, deposition positions are rejected based on this investigation, and the full-scale deposition holes are not drilled. Full-scale deposition holes that for some reason are drilled and later rejected will be backfilled with crushed rock from the site.

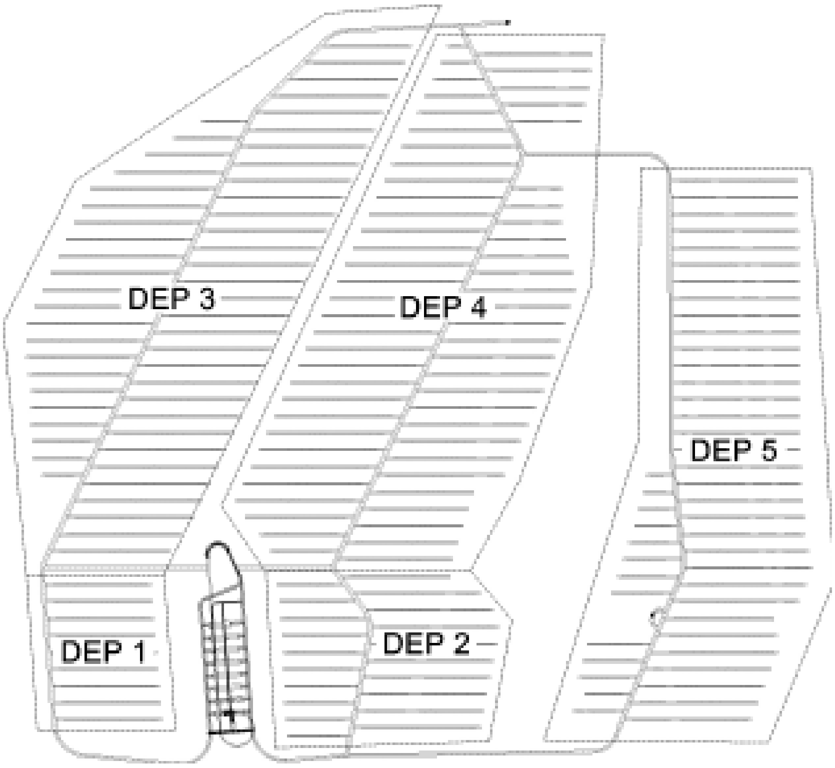


Figure 7-2. Repository layout in Forsmark showing the deposition areas /Brantberger et al. 2006/.

Table 7-2. Dimensions of deposition tunnels in Forsmark. The cross section of the deposition tunnel is estimated to 27.5 m^2 (the theoretical value showed in drawings is 25 m^2, added oversize area is 2.5 m^2). The repository layout has about 6,000 canisters.

	Deposition areas					Total
	Dep 1	Dep 2	Dep 3	Dep 4	Dep 5	
Number of deposition tunnels	9	20	53	59	46	187
Maximum length of deposition tunnels (m)	252	300	300	300	300	300
Minimum length of deposition tunnels (m)	252	144	96	48	60	48
Total length of deposition tunnels (m)	2,266	4,717	14,231	14,973	11,316	47,503
Excavated volume (m^3)[1)]	62,315	129,718	391,353	411,758	311,190	1,306,333
Theoretical number of canister positions	342	669	2,162	2,153	1,498	6,824
Number of canister positions (rejected positions 11%)[2)]	304	595	1,924	1,916	1,333	6,072

[1)] Calculated value (total length times cross area of 27.5 m^2).

[2)] According to analyses based on preliminary data.

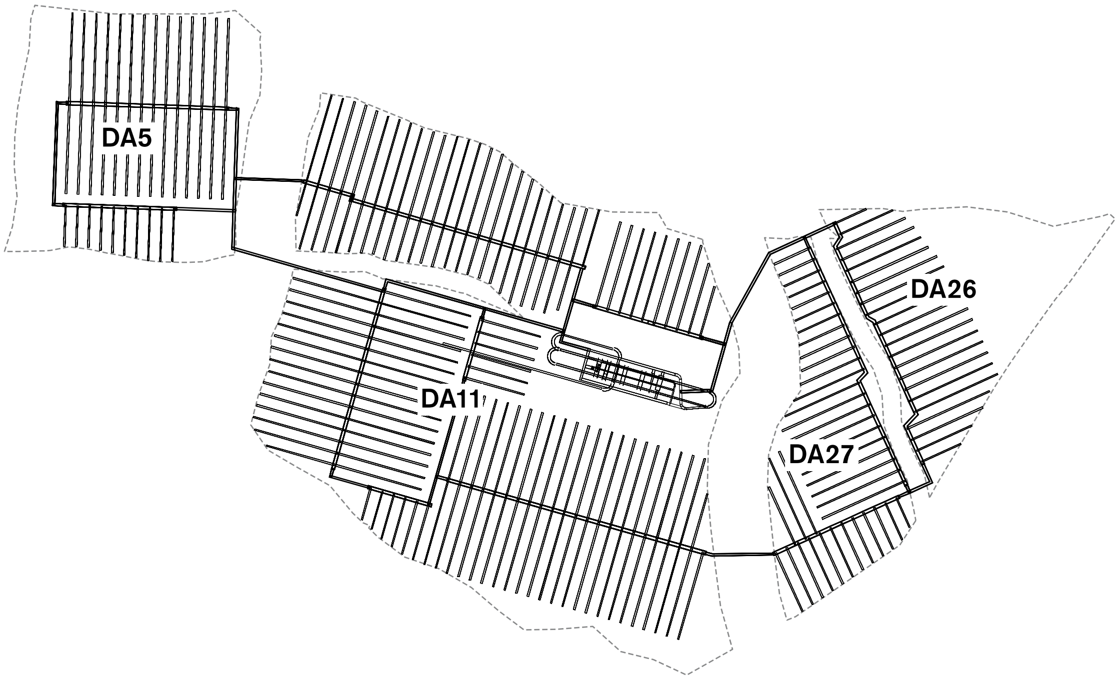


Figure 7-3. *Repository layout in Laxemar showing the deposition areas /Janson et al. 2006/.*

Table 7-3. Dimensions of deposition tunnels in Laxemar. The cross section of the deposition tunnel is estimated to 27.5 m^2 (the theoretical value showed in drawings is 25 m^2, added oversize area is 2.5 m^2). The repository layout has about 6,000 canisters.

	Deposition areas				Total
	DA5	DA 11	DA 27	DA 26	
Number of deposition tunnels	38	147	37	22	244
Maximum length of deposition tunnels (m)	296	296	296	296	296
Minimum length of deposition tunnels (m)	133	104	102	109	102
Total length of deposition tunnels (m)	9,811	37,420	7,617	5,774	60,621
Excavated volume (m^3)$^{1)}$	269,794	1,029,057	209,461	158,777	1,667,089
Theoretical number of canister positions	1,211	4,612	942	733	7,498
Number of canister positions (rejected positions 20%)$^{2)}$	969	3,690	754	586	5,998

$^{1)}$ Calculated value – total length times cross area (27.5 m^2).

$^{2)}$ According to analyses based on preliminary data.

Uncertainties

Backfilling with blocks

It has to be determined if the backfill blocks and pellets can be placed in the tunnel so that the given geometry is fulfilled under the conditions prevailing in the deposition tunnels.

This can be divided into a number of sub-uncertainties regarding:

- Placing the blocks with as small volume of slots as intended.
- Placing the pellets in the slot between the blocks and the rock with high enough density. The technique for this has not been tested and it may be difficult to gain high bulk pellet density.
- Loss in density due to piping and erosion during installation.

The average density over the cross section of a deposition tunnel will vary mainly due to the variation in tunnel geometry. It is assumed that the tunnels can be excavated so that the difference in tunnel radius is at most 0.30 m over one blasting round, which typically extends the tunnel by 4 to 7 m. Based on current assumptions for the block backfilling method, it is estimated that this would result in 70% to 86% of the tunnel cross-section being filled with blocks. It is assumed that 2% of the cross-section initially is void and the remaining volume is filled with pellets. This would result in a variation in average dry density for the tunnel cross section of 1,700 kg/m^3 to 1,850 kg/m^3 for Friedland clay and 1,840 kg/m^3 to 2,020 kg/m^3 for the example 30/70 material. The variation in backfill density between different blasting rounds will be much smaller.

7.2.3 Backfill pore geometry

The relations between void ratio, porosity, and densities are shortly described in Section 5.2.3 of this report.

Initial values

Blocks of crushed rock and bentonite

The average void ratio (e) and degree of water saturation (S_r) in the backfill is given by the average dry density, the density of the different phases and the water ratio. In this example 78% of the cross-section is assumed to be filled with blocks, 20% with pellets and 2% is void.

The dry density of the blocks is assumed to be 2,190 kg/m^3 and the water ratio is assumed to be 7%. This result in:

$e = 0.23$

$S_r = 81\%$

The dry density of the pellets is assumed to be 1,100 kg/m^3 and the water ratio is assumed to be 10%. This results in:

$e = 1.45$

$S_r = 19\%$

Blocks of Friedland clay

In this example 78% of the cross-section is assumed to be filled with blocks, 20% with pellets and 2% is void.

The dry density of the blocks is assumed to be 2,000 kg/m^3 and the water ratio is assumed to be 12%. This results in:

$e = 0.35$

$S_r = 93\%$

The dry density of the pellets is assumed to be 1,100 kg/m^3 and the water ratio is assumed to be 7%, resulting in:

$e = 1.45$

$S_r = 19\%$

Uncertainties

The general uncertainties for the backfill concepts concern the influence on water inflow on the backfilling procedure. High water inflow during the backfilling may cause processes such as piping, erosion and swelling of the backfill. These processes may lead to a decreased final density.

High water inflow to the deposition holes during backfilling also causes swelling of the buffer, wherefore it is necessary to have a high backfilling rate. This puts higher demands on the installation method and equipment that aim to place blocks with high accuracy and fill the slot between rock and blocks with pellets.

The uncertainty ranges listed below do not take the influence of water inflow into account.

Blocks of crushed rock and bentonite

The blocks are assumed to have a dry density of 2,190 ± 50 kg/m^3 with a water ratio of 7 ± 0.5%. This results in:

$e = 0.21 – 0.26$

$S_r = 67 – 99\%$

The pellets are assumed to have a dry density of 1,100 +/–50 kg/m^3 with a water ration of 10 ± 0.5% resulting in:

$e = 1.35 – 1.57$

$S_r = 17 – 20\%$

Blocks of Friedland clay

The blocks are assumed to have a dry density of 2,000 ± 50 kg/m^3 with a water ratio of 7.5 ± 0.5%. This results in:

$e = 0.32 – 0.38$

$S_r = 81 – 99\%$

The pellets are assumed to have a dry density of 1,100 +/–50 kg/m^3 with a water ratio of 7 ± 0.5%, resulting in:

$e = 1.35 – 1.57$

$S_r = 17 – 20\%$

7.2.4 Temperature

Initial values

The tunnel backfill will be in thermal equilibrium with the undisturbed host rock in the initial state. That temperature varies with repository site and disposal depth and is approximately 10–15°C. The thermal interaction between the heat-generating canister and the backfill that will take place during deposition counts as a post-closure process, even if some of that interaction will have taken place before actual closure.

Uncertainties

The backfill storage conditions, the thermal interaction between the backfill material and the backfilling equipment, and the thermal disturbance of the near field rock caused by the moving tunnel air prior to backfilling will have an influence on the backfill temperature. The uncertainty may be around 5°C. This is of no importance for the thermal evolution of the repository.

7.2.5 Water content

Initial values

Blocks of crushed rock and bentonite

For pressing the blocks, the optimal water ratio is about 7% for the planned compaction pressure. The water ratio of the pellets will be about 10%.

Blocks of Friedland clay

The block and the pellets will be given a water ratio of about 12%, which is optimal for block production. The pellets will have a water ratio of 7%.

Uncertainties

Blocks of crushed rock and bentonite

The variation in water ratio (Δw) is ± 0.5%. This is valid for both blocks and pellets.

Blocks of Friedland clay

The variation will be the same as for the mixture of crushed rock and bentonite (± 0.5%).

7.2.6 Gas content

The unsaturated pores will be filled with air and the gas content is calculated as the volume of gas divided by the total volume.

Initial values

Blocks of crushed rock and bentonite

For the blocks, the gas content is 3.6% for the given densities and water ratio. For the pellets, 49% of the total volume at the considered dry density is gas filled.

Blocks of Friedland clay

For the blocks, the gas content is 1.8% for the given densities and water ratio. For the pellets, 49% of the total volume at the considered dry density is gas filled.

Uncertainties

Blocks of crushed rock and bentonite

The variation in water ratio (Δw) is ± 0.5% in the blocks. This together with the variation in dry density yields a variation of the gas content in the blocks from 0–7%.

The gas content in the pellets varies between 47–52%

Blocks of Friedland clay

The variation in water ratio (Δw) is ± 0.5% in the blocks. This together with the variation in dry density yields a variation of the gas content in the blocks from 0–5%.

The gas content in the pellets varies between 47–52%.

7.2.7 Hydro variables (flows and pressure)

The hydro variables are water and gas flow and water and gas pressure. Initially there is no flow. The gas pressure will be atmospheric pressure in all concepts but the water pressure varies.

Initial values

Blocks of crushed rock and bentonite

The water ratio (w) of 12% of the backfill yields a negative water pressure (u) of –3,000 kPa.

Blocks of Friedland clay

The water ratio (w) of 3% of the blocks yields the same water pressure (u) as in the buffer, i.e. –160 MPa.

Relative humidity in the air-filled slots is assumed to be the same as the corresponding relative humidity (RH) in the blocks, i.e. 25%.

Uncertainties

Blocks of crushed rock and bentonite

The variation in water ratio (Δw) ± 1% yields a variation in water pressure (Δu) of ± 800 kPa.

Blocks of Friedland clay

The variation in water ratio (Δw) ± 0.5% yields a variation in relative humidity (RH) of about ± 1%, which yields a variation in water pressure (Δu) of about ± 1,800 kPa.

7.2.8 Stress state

Initial values

Concepts with pre-compacted blocks

The clay blocks are separated units with internal stresses, as described in Section 5.2.9 for the bentonite blocks and rings in the deposition holes. The same type of initial "effective stress" may thus be used for the clay blocks.

The internal stress in the Friedland clay blocks is estimated to be σ' = 43 MPa. In addition there is a vertical stress from the weight of the overburden backfill. These stresses are small compared to the internal stresses.

The initial stresses in the pellets are probably best described as the total stress originating from the weight of the overlying material.

The vertical total stress is calculated by $\sigma v = z \cdot g \cdot \rho$, where z is the distance to the roof and ρ is the bulk density.

Uncertainties

Uncertainties associated with the stress state of the backfill is not discussed in this report.

7.2.9 Backfill materials – composition and content

The potential materials included in the two backfill concepts are a natural sodium bentonite from Wyoming (MX-80), a natural calcium bentonite from Milos (Deponit CA-N), natural Friedland clay, and crushed rock from the site.

Initial values

The bentonite composition and the montmorillonite composition in MX-80 and Deponit CA-N are given in Sections 5.2.10 and 5.2.11.

The composition (wt-%) of analysed natural Friedland clay is mixed layer minerals 45%, quartz 24%, mica 13%, feldspar 5%, cabonates 2%, pyrite 1–4%, and glauconite 1%. A detailed mineralogical characterisation of the swelling component is not available. The illit/montmorillonite mixed layer material means a complex crystal structure with stacked swelling and non-swelling layers. The non-swelling structures are normally due to high layer charge and potassium fixation. The CEC of the total material is around 0.25 eq/kg and around 0.35 eq/kg for the clay fraction.

The clay formation is large and the complex mineralogy may possibly lead to varying contents of minerals. For example, no detailed information on the swelling component in the Friedland clay is available.

The crushed rock fraction is crushed rock from the excavation of the repository. The bedrock and its mineral composition are compiled in version 1.2 of the site descriptive models for Forsmark /SKB 2005b/ and Laxemar /SKB 2006h/ respectively. The granulometry of crushed and ground rock is largely determined by the rock structure and by the sieving and crushing techniques. The excavated rock is crushed to a maximum grain size of 5 mm.

The total content of backfill is determined by the excavated volumes, see Table 7-2, and estimates of left voids of about 2%, see Section 7.2.3. The estimated total volumes and amounts of backfill material in the deposition tunnels are given in Table 7-4.

Table 7-4. Total amount of backfill material in the deposition tunnels in Forsmark and Laxemar. Data are given for the two backfill concepts.

Material	**Amount (tonnes)** **Forsmark** [1]		**Laxemar** [2]	
Concept:	Blocks of crushed rock and bentonite	Blocks of Friedland clay	Blocks of crushed rock and bentonite	Blocks of Friedland clay
Crushed rock and bentonite	2,230,000		2,850,000	
Friedland clay		2,040,000		2,600,000
Pellets	287,000	287,000	367,000	367,000
Total	2,520,000	2,330,000	3,210,000	2,970,000
Amount per metre tunnel (kg/m)	53	49	53	49

[1] Forsmark: length of deposition tunnel 47,503 m, excavated volume 1,300,000 m^3.

[2] Laxemar: length of deposition tunnel 60,621 m, excavated volume 1,670,000 m^3.

Uncertainties

The composition of natural Friedland clay is relatively uncertain. See also Sections 5.2.10 (bentonite composition), 5.2.11 (montmorillonite composition) and 7.2.2.

7.2.10 Backfill pore water composition

Initial values

Pore water composition in bentonites has been discussed and described in many reports, articles and previous safety reports. In general, the pore water composition is mainly determined by:

- the charge compensating cations in the montmorillonite,
- equilibrium with the minerals in the bentonite,
- ions added with solution,
- total amount of water.

The charge compensating cations give a high cation concentration between the mont-morillonite mineral flakes. The minerals in the system lead to equilibrium concentrations for all possible ions with the available amount of water. This equilibrium may lead to quite different local conditions. At short distances between the montmorillonite flakes, the conditions will be dominated by the charge compensating cations, and at large separations between the montmorillonite flakes the conditions will be dominated by the involved minerals. The concentration of a specific ion may thereby vary several orders of magnitude.

Addition of water to the system will decrease the concentration of charge compensating cations. The equilibrium concentration with involved minerals will still be the same in volumes unaffected by the charge compensating cations, if the minerals are not completely dissolved, and the equilibrium concentration will actually increase in volumes governed by the charge compensation cations.

The mean initial pore water composition may be calculated but not directly measured. A water solution may, for example, be squeezed from the tunnel backfill material, which leads to a composition unique for the applied equilibrium condition, but not for the initial conditions.

In the initial unsaturated tunnel backfill material, the water is mainly situated between the montmorillonite surfaces, and strongly dominated by the charge compensating cations. The calculated initial concentrations cannot be used for extrapolation to conditions with other amounts of water, but the new concentrations may be calculated taking into account the equilibrium conditions.

Uncertainties

The ion equilibrium between charge compensating ions and all other ions in the system is not fully understood.

7.2.11 Structural and stray materials

Structures of concrete and steel are installed in the deposition tunnels during the operating period. Rock bolt will be used as rock support and the use of shotcrete in the deposition tunnels has to be limited and the goal is not to use any shotcrete. The rock supports will be left in the tunnels as they are essential to workers' safety whereas the other structures, for example road beds, are removed before closure of the deposition tunnel. In addition, the tunnels are cleaned with highly pressurised water before the emplacement of the backfill starts.

To prevent water inflow to the tunnels during operation, the rock surrounding the deposition tunnels will be grouted. Concrete in the grout holes are left as part of the sub-system.

The need of structural material and grouting is predicted in the design work (layout D1 /SKB 2004b, Brantberger et al. 2006, Janson et al. 2006/) and the aim is to ensure operation safety and the rock stability. The estimates are based on rock mechanical descriptions of the fracture zones and the rock in between, the service life time of the tunnels, which is five years, and on engineering judgements. The rock support solutions are site specific and vary considerably also within a site, depending on the rock quality of the different rock domains. The present estimate will be detailed and verified, for example with calculations in later design steps.

Initial values and uncertainties

Rock bolts

Rock bolts are used to tie unstable or potentially unstable rock structures in the tunnels. The limited time of operation in the deposition tunnels means that no comprehensive minimum level of supporting rock solutions are needed and a selective installation of rock bolts, complemented with rock removal and steel nets when needed.

The rock bolts in the deposition tunnel may be of the Swellex type which is anchored without grout. However in the design work, rock bolt anchored with low alkali grout has been used as a base for the estimates of the amounts of bolts needed. The rock bolts are made of steel and an example showing a possible chemical composition is given in Table 7-5. One of the primary causes of rock bolt failure is corrosion of the bolts.

Bolts are placed in the roof and walls of the caverns. The bolts, with diameters of 20–25 mm and a length of about 2.4 m, are installed in boreholes with diameters of 45 mm and are surrounded by 10 mm grout. The final recipe of low alkali anchoring grout is not available but the development is part of SKB's research program and will therefore be specified in detail at later design stages. The grout is here exemplified by a cement based low alkali type, see Table 7-7. Site specific estimates of the amounts of rock bolts needed have been done in the design work for both Forsmark and Laxemar, se Table 7-9 and Table 7-10. The estimated amounts of supporting of rock are based on the following conditions:

- technical description (rock quality, Q-system) of the rock with deformation zones at the sites,
- dimensions of tunnels and caverns,
- requirements concerning durability during construction and operation.

Wire mesh

Reinforcement wire mesh, made of hot-galvanized steel, will be used in the deposition tunnel in Laxemar to support the rock walls. The suggested nets have a mesh size of 6×8 cm and the diameter of the wire is 2.7 mm. The total area covered with wire mesh is about 220,000–290,000 m^2 with a total wire mesh weight of about 400–500 tonnes, corresponding to 7–9 kg per metre of tunnel.

Grout holes

Sections of the rock around the deposition tunnel need to be grouted, to decrease the water inflow to the tunnel. The need for injection has been estimated in the design work (layout D1).

Table 7-5. Examples of chemical composition of rock bolts.

(%-wt max)	Fe	C	Si	Mn	P	S	Cr	Cu	Ti	V	N
Swellex (EN 10025 S355JR)	Remaining	0.24	0.55	1.06	0.045	0.045	–	–	–	–	–
Rock bolt (SS-stål 2165)	Remaining	0.24	0.6	1.6	0.06	0.05					

The aims with the estimates at this stage are mainly performed as a base for judgement of groundwater composition in the repository and cost estimates. The design of the injection will be detailed at later stage of the repository design work.

In SR-Can it is assumed that low pH cement, or other low pH grouting material, will be used for grouting of deposition tunnels. The development of low pH materials is ongoing, meaning that a final recipe is not available. At this stage (Design stage D1) one recipe for a low alkali cement based injection grout, which has been tested in a pilot test in Onkalo in Finland, is used as an example. The recipe with components is given in Table 7-7 and Table 7-8. It is a mixture of the Ultrafin 16, GroutAid, and a super plasticizer (SP40).

The amount of injection needed is determined by the hydraulic properties of the surrounding rock, the groundwater composition, and a set target hydraulic conductivity of the injected rock. The target hydraulic conductivity has not been finally defined and the estimates of the amount of injection grout are done for two target levels of the hydraulic conductivity in the rock, 10^{-7} and 10^{-9} m/s. It should be noted that injection to receive the target hydraulic conductivity may need grouts and methods adapted to the specific conditions at the sites.

Grout holes are drilled with an inclination into the rock volume that needs to be grouted, and grout is injected prior to the excavation of the tunnel. Each grout hole fan array consists of about 20 grout holes, 0.05–0.06 m in diameter and 20 m in length. The grout holes are part of the deposition tunnel sub-system and will be left filled with grout. The grout in rock fractures is associated with the geosphere.

The grouting of the deposition tunnels in Forsmark will be performed in a selective manner meaning that the need of grouting will always be based on water inflow to observation boreholes drilled in the tunnel front prior to every third round of shots. The present estimates of the volumes and amounts of grout and its major components around the deposition tunnels in Forsmark are given in Table 7-6. The estimates at this stage, which are based on information on the target hydraulic conductivity and hydraulic conditions in the rock volume surrounding the deposition tunnels, as well as on information on the groundwater composition, are very rough and more detailed estimates will be made as the design work progress. The target level 10^{-7} m/s means that almost no grouting is needed in the deposition tunnels.

The deposition area in Laxemar is located in two different rock domains (2/3 of the deposition tunnels are located in domain M and 1/3 in rock domain A). The need of grouting will be based on water inflow measurements in grout holes drilled to explore the rock. If there is a need, more grout holes are drilled. Otherwise the exploratory grout holes are plugged with grout. To obtain the target hydraulic conductivity of 10^{-7} m/s, 5% of the total deposition tunnel length has to be grouted in rock domain A and 2.5% in rock domain M. To obtain a target hydraulic conductivity of 10^{-9} m/s, 60% of the total deposition tunnel length has to be grouted in rock domain A and 30% in rock domain M. The estimated amounts of grout needed in Laxemar are given in Table 7-6.

Table 7-6. Amount of structural materials in the deposition tunnels.

	Forsmark (tunnel length 47,503 m)		**Laxemar (tunnel length 60,621 m)**	
	Total amount (tonnes)	**Amount per metre tunnel (kg/m)**	**Total amount (tonnes)**	**Amount per metre tunnel (kg/m)**
Steel				
Rock bolts	170–290	4–6	600–780	10–130
Nets	–	–	400–540	7–9
Grout or concrete				
Anchoring grout (rock bolts)	66–110	1–2	480–630	8–10
Injection grout (in grout holes)	0–450	0–9	1,200–2,400	19–39
Grout in rock fractures	0–1,000	0–20	420–6,800	69–110

Table 7-7. Examples of recipes – low alkali grouts to be used for anchoring of rock bolts and grouting /Sievänen et al. 2004/.

Component	Anchoring grout for rock bolts	Injection grout	Comment
Water (kg)	696	599	
Ultrafin 16 (kg)	–	299	Micro cement. Sulphate resistant Portland Cement Density: 800–1,500 kg/m^3 Composition is given in Table 7-8.
White cement (kg)	596	–	Low alkali Portland Cement (Aalborg) Density: 1,100 kg/m^3 Composition is given in Table 7-8.
Grout Aid (kg)	–	419	Dispersed silica fume, (50 wt-% SiO_2 , 50 wt-% water) Density: 1,350–1,410 kg/m^3
Silica Fume (kg)	255		Consists primarily of amorphous non-crystalline silicon dioxide (SiO_2)
SP 40 (kg)	2	11	Super plastiziser Density: 1,260 kg/m^3
Density (kg/m^3)	1,549	1,328	

Table 7-8. Chemical composition of low alkali grout components.

Product name	Type	CaO wt-% (dry)→	SiO_2	Al_2O_2	Fe_2O_3	SO_3	Na_2O	Others
Ultrafin 16	Sulphate resistant Portland cement	64.8	22.3	3.4	4.3	2.4	–	2.8
White cement	Low alkali cement							

Table 7-9. Deposition tunnels in Forsmark – rock bolts and anchoring grout with components.

	Total 1)		Per metre deposition tunnel	
	Minimum	Maximum	Minimum	Maximum
Rock bolts				
Number of rock bolts	18,000	30,000	$3.7 \cdot 10^{-1}$	$6.4 \cdot 10^{-1}$
Weight (tonnes)	170	290	$3.6 \cdot 10^{-3}$	$6.1 \cdot 10^{-3}$
Anchoring grout				
Volume (m^3)	43	73	$9.0 \cdot 10^{-4}$	$1.5 \cdot 10^{-3}$
Weight (tonnes) 2)	66	110	$1.4 \cdot 10^{-3}$	$2.4 \cdot 10^{-3}$
White cement 3)	25	43	$5.4 \cdot 10^{-4}$	$9.1 \cdot 10^{-4}$
Silica 3)	11	19	$2.3 \cdot 10^{-4}$	$3.9 \cdot 10^{-4}$
SP40	0.085	0.15	$1.8 \cdot 10^{-6}$	$3.1 \cdot 10^{-6}$

1) Total length of deposition tunnels: 47,503 m.

2) Including water.

3) Excluding water.

Table 7-10. Deposition tunnels in Laxemar – rock bolts and anchoring grout.

	Total [1]		Per metre deposition tunnel	
	Minimum	Maximum	Minimum	Maximum
Rock bolts				
Number of rock bolts	102,000	133,000	1.7	2.2
Weight (tonnes)	600	780	$9.9 \cdot 10^{-3}$	$1.3 \cdot 10^{-2}$
Anchoring grout				
Volume (m^3)	310	410	$5.2 \cdot 10^{-3}$	$6.7 \cdot 10^{-3}$
Weight (tonnes) [2]	480	630	$8.0 \cdot 10^{-3}$	$1.0 \cdot 10^{-2}$
White cement [3]	190	240	$3.1 \cdot 10^{-3}$	$4.0 \cdot 10^{-3}$
Silica [3]	80	100	$1.3 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$
SP40	0.63	0.81	$1.0 \cdot 10^{-5}$	$1.3 \cdot 10^{-5}$

[1] Total length of deposition tunnels: 60,621 m.

[2] Including water.

[3] Excluding water.

Table 7-11. Deposition tunnels in Forsmark – grout in grout holes and rock fractures (the fractures belongs to the geosphere and are not part of this sub-system).

	Total [1]		Per metre deposition tunnel	
	Grouting level 1 (rock conductivity 10^{-7} m/s)	Grouting level 2 (rock conductivity 10^{-9} m/s)	Minimum (min of grouting level 1)	Maximum (max of grouting level 2)
Number of injection holes	no grouting needed	4,900–5,200	no grouting needed	
Grout in injection holes				
Volume (m^3)	–	310–340	–	$7 \cdot 10^{-3}$
Weight (tonnes) [2]	–	420–450	–	$9 \cdot 10^{-3}$
Cement [3]		94–100		$2 \cdot 10^{-3}$
Silica [3]		66–70		$1 \cdot 10^{-3}$
SP40		3.4–3.7		$7 \cdot 10^{-5}$
Grout in fractures				
Volume (m^3)	–	150–780	–	$2 \cdot 10^{-2}$
Weight (tonnes) [2]	–	190–1,000	–	$2 \cdot 10^{-2}$
Cement [3]		44–230		$5 \cdot 10^{-3}$
Silica [3]		30–160		$3 \cdot 10^{-3}$
SP40				$8 \cdot 10^{-4}$

[1] Total length of deposition tunnels: 47,503 m.

[2] Including water.

[3] Exclusive water.

Table 7-12. Deposition tunnels in Laxemar – grout in grout holes and rock fractures (the fractures belongs to the geosphere and are not part of this sub-system).

	Total [1]		Per metre deposition tunnel	
	Grouting level 1 (rock conductivity 10^{-7} m/s)	**Grouting level 2 (rock conductivity 10^{-9} m/s)**	**Minimum (min of grouting level 1)**	**Maximum (max of grouting level 2)**
Number of boreholes	22,000–33,000	26,000–45,000		
Grout in injection holes				
Volume (m^3)	890–1,300	1,100–1,800	$1.5\cdot10^{-2}$	$3.0\cdot10^{-2}$
Weight (tonnes) [2]	1,200–1,800	1,400–2,400	$1.9\cdot10^{-2}$	$3.9\cdot10^{-2}$
Cement [3]	270–390	310–540	$4.4\cdot10^{-3}$	$8.9\cdot10^{-3}$
Silica [3]	190–280	220–380	$3.1\cdot10^{-3}$	$6.2\cdot10^{-3}$
SP40	10–14	12–20	$1.6\cdot10^{-4}$	$3.3\cdot10^{-4}$
Grout in fractures				
Volume (m^3)	320–590	2,600–5,100	$5.2\cdot10^{-3}$	$8.4\cdot10^{-2}$
Weight (tonnes) [2]	420–780	3,400–6,800	$6.9\cdot10^{-2}$	$11\cdot10^{-2}$
Cement [3]	94–180	760–1,500	$1.6\cdot10^{-3}$	$2.5\cdot10^{-2}$
Silica [3]	66–120	530–1,100	$1.1\cdot10^{-3}$	$18\cdot10^{-3}$
SP40	3.5–6.4	28–56	$5.7\cdot10^{-4}$	$9.3\cdot10^{-4}$

[1] Total length of deposition tunnels: 60,621 m.

[2] Including water.

[3] Eexclusive water.

Stray materials

Stray materials are materials, except for barriers and construction materials, which are introduced into the repository during operation. Examples of stray materials, other than steel and concrete, are spillage of oil and remainders of explosives.

Spillage of oil for lubrication and hydraulic systems would occur for any excavation method, but different methods would have different opportunities by design to mitigate spillage. Spillage of oil is very much a matter of preventive maintenance, age of equipment, operator skill etc. To mitigate environmental impacts by spillage, the following actions are viable:

- Design of equipment where the machines are equipped with trays that collects oil spillage.
- Absorbing materials at the rigs to be used at major spillages.
- Selection of oil that is degradable. Most of the environment-friendly oils are based on biological oils and alcohols from the mineral oils. True biological oils, based on rape-oil, degrade in nature within a few weeks, synthetic oils within a few months and mineral oils within several years.

Drill and blast excavation include spillage or remainder of explosives, detonators, etc. On average this spillage or remainder comprises 5–10% of the total consumption. The environmental concern is the emission of nitrogen, the main compound in explosives. The major bulk of the spillage will assemble in the muck, and the major part will be transported out with the muck and in addition, parts will be released with the drainage water as the compound is soluble in water. In case the rock muck is used for backfill, these are rinsed with water in connection with the processing. The drainage water can be processed by standard technology to remove the excess nitrogen.

The major share of all spillage will assemble at the tunnel floor and is removed as the roadbed is removed from the tunnel before backfilling. A rough estimate is that 1% of the oil and explosive spillage is left in the deposition tunnel after cleaning procedures prior to the backfilling.

Other materials that will be left are anchoring bolts for e.g. ventilation, cables etc, corrosion products, rests of concrete constructions, human waste products , for example urine. The estimate of human waste left is based on the assumptions that 100 employers work in the deep repository during the 40 years of operation that urinate 0.25 litre per day in the tunnels and that the content of urea in the urine is 2 wt-%. The amount of urine is reduced by 99% in the cleaning procedures prior to the backfilling.

The estimates of stray materials left in the deposition tunnels are given in Table 7-13. The numbers in the table is based on an update of earlier inventory of stray materials that has been done during 2005 (the report is an internal document). The values presented in the table are very uncertain, mainly since the routines for decommissioning and cleaning of the tunnels have not been specified at this stage (design D1).

Uncertainties

The inventory of materials to be used is rather well known where as the estimates of the amounts left in the repository are more uncertain at this stage.

Table 7-13. Estimates of stray materials left in the deposition tunnels given as g/m tunnel (not site specific). Estimates of the total amounts in Forsmark and Laxemar are presented.

Material	Component	Amount per metre tunnel (g/m)	Total amount (kg)	
			Forsmark [1]	Laxemar [2]
Detonator with conductor	Aluminium	0.8	40	50
	Plastic	5	200	300
Explosives	NOx	0.2	10	10
	Nitrate	50	2,000	3,000
Bolts	Steel	1,000	50,000	60,000
Concrete constructions	Concrete	40	2,000	2,000
Tyre wear	Rubber	0.1	5	7
Exhausts	NOx	–		
	Particles	–		
Detergents and degreasing compounds		0		
Hydraulic and lubrication oil		5	200	300
Diesel oil		–		
Battery acid		–		
Metal chips		0.1	5	6
Wood chips	Wood	0.3	10	20
Corrosion products	Rust	80	4,000	5,000
Urine	Urea	0.8	40	50
Other human waste	Organics	–		
Ventilation air	Organics	0.4	20	20

1) Forsmark: length of deposition tunnels 47,503 m.

2) Laxemar: length of deposition tunnels 60,621 m.

8 Backfill of other repository cavities

8.1 General

Other repository cavities, except for deposition tunnels, for example access ramp and shafts, transport and main tunnels, ventilation shafts, and central areas (see Figure 8-1) that together make up the necessary space for access to and operation of the underground area and its deposition areas will be backfilled during decommissioning.

As part of the decommissioning, installations and building components will be stripped out and transported up to the surface. The installations are removed to reduce the amount of organic material, metals, etc in the repository.

It is assumed, for the purpose of SR-Can, that similar excavation methods as for the deposition tunnels are used also for the excavation of the other cavities, and it is further assumed that the same backfill concept is applied, see Chapter 7. In addition, it is assumed that the working methods worked out for application of the backfill in the deposition tunnels are used.

The backfill of these cavities are not described or analysed in detail in SR-Can.

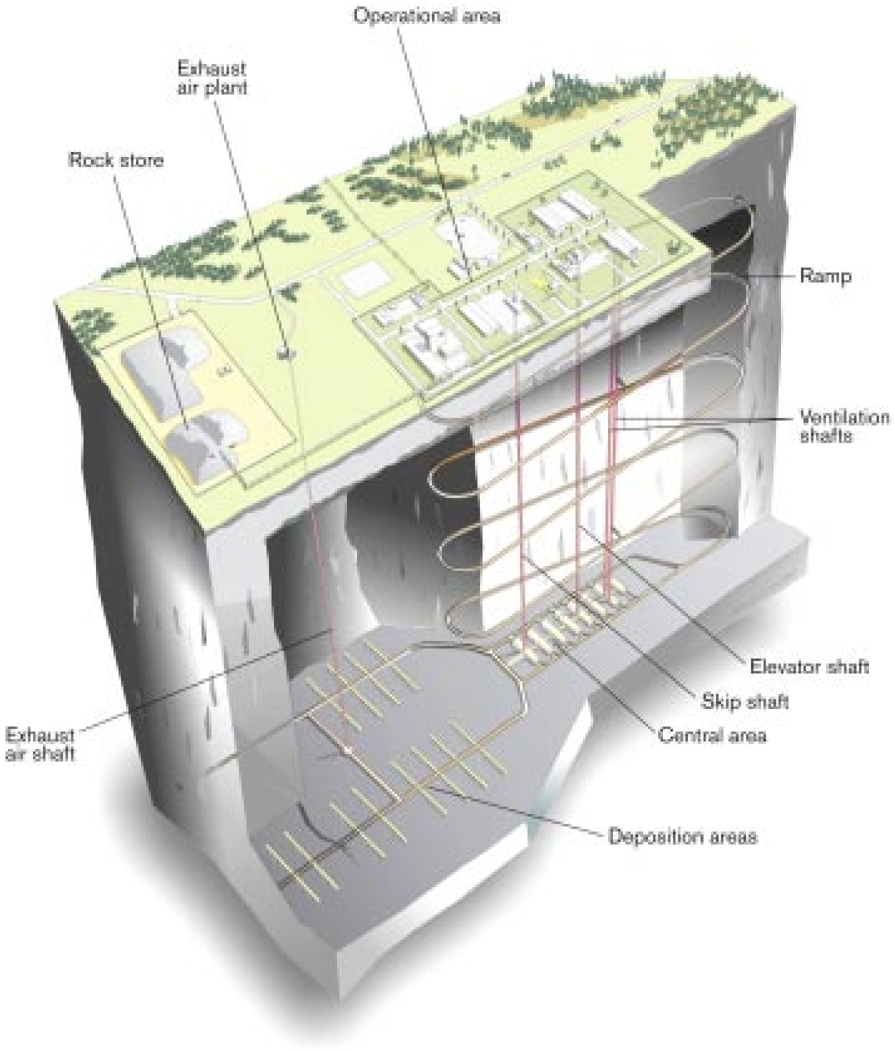


Figure 8-1. *Generic layout of deep repository for spent nuclear fuel.*

8.2 Variables

8.2.1 Overview

The other repository cavities are mainly constrained in space by the rock surrounding the cavities and interfaces with each other. For example the main tunnels in the deposition area have interfaces to the plugs at the ends of the deposition tunnels.

The backfill in the cavities is delimited by the variable backfill geometry. The backfill is characterised thermally by its temperature. Hydraulically it is characterised by the hyrdovariables (pressure and flow). Mechanically, the backfill is characterised by the stress state. The chemical state of the backfill is defined by the material composition, water composition, and construction and stray materials.

All variables are defined in Table 8-1. The values of some of the variables depend on the density of the different phases. The following values have been used: density of water (ρ_w) is 1,000 kg/m^3, density of clay solids (ρ_{cs}) is 2,780 kg/m^3, and density of crushed rock solids (ρ_{rs}) is 2,700 kg/m^3.

8.2.2 Backfill geometry

The backfill geometry is determined by the dimensions of the different cavities. The dimensions of all cavities are described in detail in the facility description /SKB 2002/, which will be updated at certain intervals. The dimensions of the different cavities presented here are preliminary, based on the equipment planned to be used at present, and will be optimised. An overview of the main dimensions and excavated volumes are given in Table 8-2.

The repository can be approached through the ramp or through skip and elevator shafts. The ramp is 7 m high, 7 m wide and has a number of passing places, 8 m high and 12 m wide, as well as other niches. The total length of the ramp is 5,000 m. Five shafts connect the repository and the surface, a skip shaft, three ventilation shafts and an elevator shaft. The shafts are all 400–500 m deep, depending on site, and the diameter is 5.5 m in the skip shaft and elevator shaft whereas the diameters of the ventilation shafts are 3.5, 3 and 2.5 m, respectively.

Table 8-1. Variables for backfill of other repository cavities.

Variable	Definition
Backfill geometry	Geometric dimensions for backfill in repository cavities (excluding deposition holes and deposition tunnels). A description of e.g. interfaces towards plugs in deposition tunnels and towards the geosphere.
Backfill pore geometry	Pore geometry as a function of time and space in backfill in repository cavities (excluding deposition holes and deposition tunnels). The porosity, i.e. the fraction of the volume that is not occupied by solid material, is often given.
Temperature	Temperature as a function of time and space in backfill in repository cavities (excluding deposition holes and deposition tunnels).
Hydrovariables (pressures and flows)	Flows and pressures of water and gas as a function of time and space in backfill in repository cavities (excluding deposition holes and deposition tunnels).
Stress state	Stress state in backfill in repository cavities (excluding deposition holes and deposition tunnels).
Backfill materials, composition and content	Chemical composition and content (including any radionuclides) in time and space of the backfill in repository cavities (excluding deposition holes and deposition tunnels). This variable also includes material sorbed to the surface.
Backfill pore water composition	Composition of the pore water (including any radionuclides and dissolved gases) in time and space in backfill in repository cavities.
Structural and stray materials	Chemical composition and quantity of structural (rock bolts, filling material in bore-holes for grouting, nets, shotcrete) and stray materials in repository cavities (excluding deposition holes and deposition tunnels).

Table 8-2. Overview of the dimensions of the other cavities in Layout D1 in Forsmark and Laxemar.

Repository cavity	Width or diameter (m)	Height (m)	Area (m²) *	Forsmark		Laxemar	
				Length (m²)	Volume (m³) **	Length (m²)	Volume (m³) **
Main tunnel	10	7	72.6	5,030	388,000	6,500	430,000
Transport tunnel	7	7	50.6	2,676	145,000	4,600	213,000
Ramp	5.5	6	36.3		145,000		182,000
Central area	3–14	3–16			154,000		154,000
Shafts	2.5–5.5	–		400	33,000	500	41,000
Total					865,000		1,020,000

* Theoretical value showed in drawings plus 10% added oversize.

** Calculated, tunnel length times area.

The central area is divided into different vaults, each designed for its intended functions. The vaults are situated on transverse links between parallel transport tunnels. The cross section of the vaults varies from 6 to 15 m in width and from 4 to 15 m in height. The main tunnels in the central area are 10 m wide and 7 m high and there is also additional tunnels with smaller cross sections. An 18.5 m deep silo for excavated rock mass with a diameter of 7.7 m is located close to the central area. The silo is connected to the deposition areas with ramps and tunnels.

The cross sections of the tunnels in the deposition areas take account of all planned types of transport vehicles. In most sections of these tunnels, the transport and handling of copper canisters have determined the size. One of the ventilation shafts is located to the deposition area.

8.2.3 Backfill pore geometry

See Section 7.2.3.

8.2.4 Temperature

See Section 7.2.4.

8.2.5 Hydro variables (flows and pressure)

See Section 7.2.7.

8.2.6 Stress state

See Section 7.2.8.

8.2.7 Backfill materials – composition and content

For the purpose of SR-Can it is assumed that the backfill concept applied for the deposition tunnels is applied also for the other cavities. The materials included in the two potential backfill concepts are either: a mixture of bentonite (MX-80 or Deponit CA-N) and crushed rock from the site or Friedland clay, see also Section 7.2.9.

Initial values

The material compositions are given Section 7.2.9.

The total content of backfill is determined by the excavated volumes, see Table 8-2, and estimates of left voids in the applied backfill concept, see Section 7.2.3. The estimated amounts of backfill material in the other caverns are shown in Table 8-3.

8.2.8 Backfill pore water composition

See Section 7.2.10.

8.2.9 Structural and stray materials

As part of the decommissioning of the facility, and as for the deposition tunnels, installations and building components will be stripped out prior to the backfilling of the underground facility. Materials like road beds will be removed but supporting of rock, for example shotcrete, nets, and rock bolts, as well as grouting in grout holes will be left.

The need of structural material is predicted in the design work (layout D1 /SKB 2004b, Brantberger et al. 2006, Janson et al. 2006/) and the aim is to ensure the rock stability and the operation safety. The estimates are based on rock mechanical descriptions of the fracture zones and the rock in between, the life time of the tunnels, as well as engineering judgements. The designed service-life is 100 years for all cavities except deposition tunnels. Estimates of the amounts of rock supporting are made in design work and are based on empirical methods. The estimates will be verified at later stages in the design work. At the present stage (D1) the uncertainties are very large.

Besides the construction materials, stray materials will be present in the deep repository in the form of spillage and waste products from machine use, contaminants from blasting, human refuse and materials introduced via the ventilation air, etc. The amounts of stray material left in the repository are very much dependent on requirements on stripping and cleaning of the repository cavities before the backfilling. These requirements may be detailed at later stages.

Initial values

Rock bolts

Rock bolts are used to tie unstable or potentially unstable rock structures in the cavities. The service life time in the cavities means that a comprehensive minimum level of supporting rock solutions is needed, comprising selective installation of rock bolts and 50 mm thick fibre reinforced shotcrete. An alternative to the shotcrete is supporting nets of steel or plastics.

Table 8-3. Total amount of backfill material in the other caverns in Forsmark and Laxemar.

Material	**Amount (tonnes)** **Forsmark** [1]		**Laxemar** [2]	
Concept:	Blocks of crushed rock and bentonite	Blocks of Friedland clay	Blocks of crushed rock and bentonite	Blocks of Friedland clay
Crushed rock and bentonite	1,479,000		1,741,000	
Friedland clay		1,350,000		1,590,000
Pellets	190,400	190,400	224,000	224,000
Total	1,669,000	1,541,000	1,966,000	1,814,000

[1] Excavated volume in Forsmark: 865,700 m^3.

[2] Excavated volume in Laxemar: 1,019,380 m^3.

Rock bolt anchored with low alkali grout has been used as a base for the estimates of the amounts of bolts needed. The rock bolts are made of steel and an example showing a possible chemical composition is given in Table 7-5. One of the primary causes of rock bolt failure is corrosion of the bolts. The bolts are installed in the roof and walls of the cavities. The bolts are installed in boreholes with a diameter of 45 mm, the bolts have a diameters of 25 mm, a length of 2.4 or 3 m and are surrounded by 10 mm grout. The final recipe of low alkali anchoring grout is not available but the development is part of SKB's research program and will therefore be specified in detail at later design stages. The grout is exemplified by a cement based low alkali type, see Table 7-7. The estimated amounts of supporting of rock are based on the following conditions:

- technical description (rock quality, Q-system) of the rock with deformation zones,
- dimensions of tunnels and caverns,
- requirements concerning durability during construction and operation.

Shotcrete

The ceiling and walls in the cavities are reinforced with shotcrete. The average thickness of the shotcrete is on the order of 50 mm, except for locations passing through fracture zones where the thickness of the shotcrete is 100 mm. No shotcrete is applied in the ventilation shafts.

The shotcrete is low alkali concrete. The final recipe is not developed and decided yet but a possible solution, which is being developed by SKB, is used as an example at this stage of the repository design work (D1). It is a mixture of ordinary Portland Cement and Silica Fume. In addition the shotcrete contains about 70 kg reinforcing steel fibres per m^3, see Table 8-4.

The estimated total amount of shotcrete in the other cavities is for Forsmark 24,000–28,000 tonnes and for Laxemar 26,000–43,000 tonnes.

Table 8-4. Examples of recipes – low alkali grout and shotcrete /Sievänen et al. 2004/.

Component	Amout (kg)			Comment
	Anchoring grout for rock bolts	Injection grout	Shotcrete	
Water	696	599	214	
Cement	–	–	306	Ordinary Portland Cement
Ultrafin 16	–	299		Micro cement. Sulphate resistant Portland Cement Density: 800–1,500 kg/m^3 Composition is given in Table 7-8.
White cement	596	–	–	Low alkali Portland Cement (Aalborg) Density: 1,100 kg/m^3
Grout Aid	–	419	–	Dispersed silica fume, (50 wt% SiO_2 , 50 wt% water) Density: 1,350–1,410 kg/m^3
Silica Fume	255		204	Dispersed silica fume, (50 wt% SiO_2 , 50 wt% water) density 1,350–1,410 kg/m^3
SP 40	2	11	7	Super plastiziser, density 1,260 kg/m^3
Ballast	–	–	1,500	
Fibres	–	–	70	Steel fibres
Density	1,549	1,328	2,301	
Vct			214	

Table 8-5. Examples of chemical composition of grout and shotcrete components.

Product name	**Type**	**CaO wt-% (dry)→**	**SiO_2**	**Al_2O_2**	**Fe_2O_3**	**SO_3**	**Na_2O**	**Others**
Ultrafin 16	Sulphate resistant Portland cement	64.8	22.3	3.4	4.3	2.4	–	2.8
White cement	Low alkali cement							
Cement	Ordinary Portland Cement /Möller et al. 1982/	64–67	20–25	3–7	2–4			

Table 8-6. Other caverns in Forsmark – grout, rock bolts and shotcrete (the grout in the fractures belongs to the geosphere and are not part of this sub-system).

	Total	
	Minimum	**Maximum**
Grout in boreholes	**grouting level 1 (rock conductivity 10^{-7} m/s)**	**grouting level 2 (rock conductivity 10^{-9} m/s)**
Volume (m^3)	41	120–130
Weight (tonnes) $^{1)}$	54	160–170
Cement $^{2)}$	12	36–39
Silica $^{2)}$	9	25–27
SP40	0.5	1.3–1.4
Grout in fractures	**grouting level 1 (rock conductivity 10^{-7} m/s)**	**grouting level 2 (rock conductivity 10^{-9} m/s)**
Volume (m^3)	16–170	38–300
Weight (tonnes) $^{1)}$	21–230	50–400
Cement $^{2)}$	5–51	11–91
Silica $^{2)}$	3–36	8–63
SP40	0.2–2	0.4–3.3
Rock bolts		
Volume (m^3)	92	115
Weight (tonnes)	370	460
Anchoring grout		
Volume of grout (m^3)	92	120
Weight (tonnes) $^{1)}$	140	180
White cement $^{2)}$	55	69
Silica $^{2)}$	23	29
SP40	0.18	0.23
Shotcrete		
Volume (m^3)	10,000	12,200
Weight (tonnes) $^{1)}$	24,000	28,000
Cement $^{2)}$	3,200	3,700
Silica $^{2)}$	2,100	2,500
SP40	72	85
Fibres	720	850

$^{1)}$ Including water.

$^{2)}$ Exclusive water.

Table 8-7. Other caverns in Laxemar – grout, rock bolts and shotcrete (the grout in the fractures belongs to the geosphere and are not part of this sub-system).

	Total	
	Minimum	**Maximum**
Grout in boreholes	**grouting level 1 (rock conductivity 10^{-7} m/s)**	**grouting level 2 (rock conductivity 10^{-9} m/s)**
Volume (m^3)	280–510	330–730
Weight (tonnes) 1)	370–680	440–960
Cement 2)	82–150	99–220
Silica 2)	58–100	69–150
SP40	3–6	4–8
Grout in fractures	**grouting level 1 (rock conductivity 10^{-7} m/s)**	**grouting level 2 (rock conductivity 10^{-9} m/s)**
Volume (m^3)	220–540	1,000–2,100
Weight (tonnes) 1)	300–720	1,400–2,800
Cement 2)	67–160	300–640
Silica	47–110	210–450
SP40	2–6	11–23
Rock bolts		
Volume (m^3)	59	76
Weight (tonnes)	460	590
Anchoring grout		
Volume (m^3)	190	440
Weight (tonnes) 1)	300	680
White cement 2)	120	260
Silica 2)	49	110
SP40	0.39	0.87
Shotcrete		
Volume (m^3)	11,700	19,400
Amount (tonnes) 1)	26,100	43,300
Cement 2)	3,600	5,900
Silica 2)	2,400	4,000
SP40	82	140
Fibres	820	1,400

1) Including water.
2) Exclusive water.

Stray materials

More activities take place in the other cavities, especially in the central area, than in the deposition area, and the requirements on decommissioning and cleaning is expected to be less in this area. The estimates of total amounts of stray materials left in other cavities are given in Table 8-8. The numbers in the table are based on an update of the inventory of stray materials that has been done during 2005 (the report is an internal SKB document). The estimates for the other cavities are more general than for the deposition tunnels but the inventory is judged to be comprehensive and include all potential stray materials. The inventory is not site specific and it can be concluded that this fact has no significance.

Table 8-8. Estimates of stray materials left in the other cavities.

Material	Component	Total amount (kg)
Detonator with conductor	Aluminium	20
	Plastic	100
Explosives	NOx	4
	Nitrate	1,000
Bolts	Steel	50,000
	Concrete	30,000
Road beds	Concrete	3,000
	Aphalt	1,000
Concrete constructions	Concrete	3,000
Tyre wear	Rubber	30
Exhausts	NOx	600
	Particles	20
Detergents and degreasing compounds		*
Hydraulic and lubrication oil		50
Diesel oil		*
Battery acid		*
Metal chips		2
Wood chips	Wood	3
Corrosion products	Rust	200
Urine	Urea	300
Other human waste	Organics	500
Ventilation air	Organics	10

* Finite, not quantified, amount.

9 Plugs

9.1 General

This sub-system comprises the deposition tunnel plugs or seals in the deposition tunnels as well as all other potential seals or plugs in the repository.

The plugs in the repository are not analysed in SR-Can. A description of one possible solution of the deposition tunnel plugs are given below. The final design of the plugs will be included in later design steps.

Operating plugs

The backfilled deposition tunnel needs to be sealed awaiting the backfilling of the main tunnel. The operating plug must be sized to prevent water flow and to be strong enough to withstand the combined pressure from groundwater and the swelling of the backfill. The operating plug will be left in the repository at its closure although they have no long-term safety functions. The design of the plug is dependent on the surrounding rock properties and the selection of backfill concept. Two major types are presently discussed, reinforced plugs and friction plugs.

The type used as an example in this study is a reinforced plug grouted with low pH cement. The design of the plug considered is very similar to the reinforced plugs installed in the Prototype Repository in Äspö HRL /Johannesson et al. 2004/. At installation of the plug a slot is excavated into the rock wall by boring and blasting and a retaining wall is erected at the tunnel end, to prevent the backfill material from falling into the main tunnel during the grouting of the reinforced plug. The design of the plug is shown in Figure 9-1.

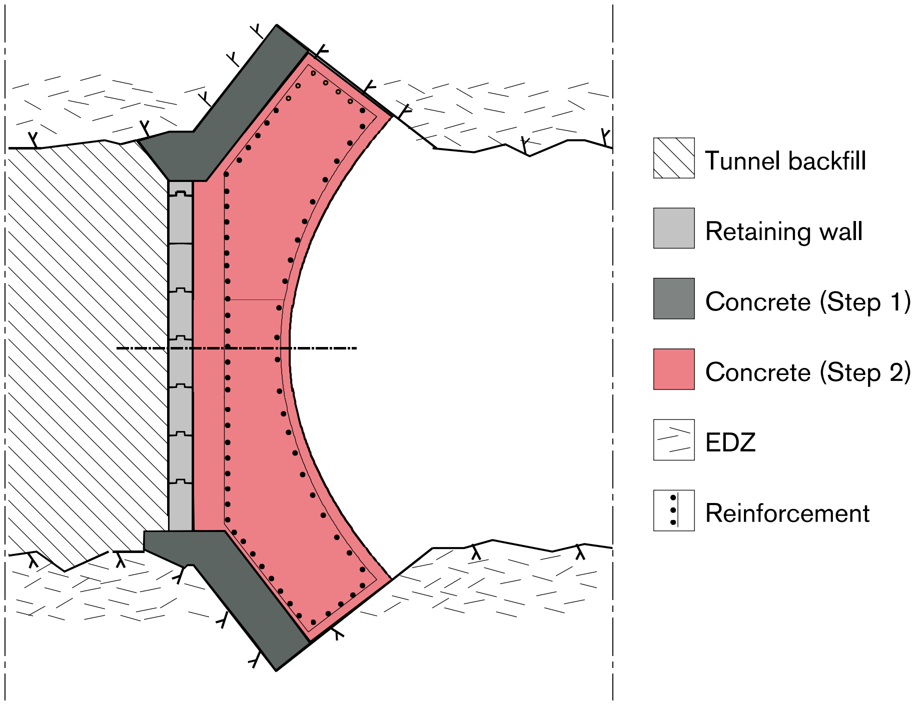


Figure 9-1. *The design of the deposition tunnel plug, schematic drawing.*

Permanent plugs

Permanent plugs with a long-term safety function, e.g. between deposition areas, are considered as a possibility. The need of permanent plugs will be investigated in later site specific safety analysis and detailed design of the plugs will be developed thereafter.

Pugs for preventing human intrusion and final sealing

When it comes to final sealing and closure of the repository plugs will be installed with the main aim to prohibit intrusion of any kind. The function and design of such plugs are subject to present investigations. Awaiting the results of these investigations no plugs for final sealing is considered in the repository.

9.2 Variables

9.2.1 Overview

The plug in a deposition tunnel as it is delimited by the variable plug geometry is characterized thermally by its temperature and hydraulically by the hydro variables (pressure and flow). Mechanically, the plug is characterised by the stress state. The chemical state of the buffer is defined by the composition and content of used materials and the pore water composition. The variables are defined in Table 9-1.

9.2.2 Plug geometry

Initial value

Operational seals

Each deposition tunnel will be plugged with an operational seal or plug to complete the backfilling of the tunnel. The height and width of the plug is determined by the dimensions of the tunnel, see Table 9-2. Prior to the grouting of the main body of the plug a slot has to be excavated in to the rock at the tunnel end and a retaining wall is installed during the backfilling of the tunnel to prevent the backfill from falling out.

Table 9-1. Variables for plugs.

Variable	Definition
Plug geometry (and pore geometry)	Geometric dimensions for plugs. A description of e.g. interfaces towards backfill in tunnels and the geosphere. Pore geometry as a function of time and space in plugs. The porosity, i.e. the fraction of the volume that is not occupied by solid material is often given.
Temperature	Temperature as a function of time and space in plugs.
Hydro variables (pressures and flows)	Flows and pressures of water and gas as a function of time and space in plugs.
Stress state	Stress state as a function of time and space in plugs.
Materials – composition and content	Chemical composition and content of the materials in the plugs (including any radionuclides) in time and space. This variable also includes material sorbed to the surface.
Pore water composition	Composition of the pore water (including any radionuclides and dissolved gases) in time and space in plugs.

Table 9-2. Dimensions of the plugs in the deposition tunnels.

Dimensions	Retaining wall	Main plug body	Slot
Height (m)	5.4	5.4 (+0.5/–0)	–
Width (m)	4.9	4.9 (+0.5/–0)	–
Thickness (m)	0.3	1.2–1.4	–
Depth (m)	–	–	1.0 ± 0.5

A slot in the rock wall that has a triangular cross section, with a 90° angle at its inner end and an average depth of 1.5 m is excavated in a way that ensures that no additional excavation damage is obtained in the rock and a concrete abutment is cast around the tunnel periphery.

The 0.3 m thick retaining wall is made of seven prefabricated reinforced concrete beams (0.3 m wide and 0.6 m high). The wall has a volume of 5.9 m^3.

The main body of the plug is about 1.2–1.4 m thick and has a total volume of about 60–70 m^3.

Uncertainties

The geometry of the plug is determined by the geometry of the tunnel.

9.2.3 Temperature

Initial value

The plugs are in thermal equilibrium with the undisturbed host rock in the initial state. That value varies with repository site and disposal depth and is approximately 10–15°.

Uncertainties

Potential effects from hydration of the concrete on the temperature are very small. The plug is cooled during hydration to prevent fracturing.

9.2.4 Hydro variables (flows and pressure)

Initial value

Initially there is no water flow through the plug. The plug is not gas tight.

Uncertainties

The concrete changes its volume with changed temperature and the reinforcement is assumed to make the volume changes elastic, i.e. no fractures are created in the plug body. But this may happen in reality. The consequences can be evaluated in terms of water or gas transport capacity and thereby compared to the acceptable values.

9.2.5 Stress state

Initial value

Initially the plug provides a mechanical support to the backfill material. This pressure is initially a couple of hundred kPa.

The plug will be designed to sustain the hydraulic pressure in and the swelling pressure of the backfill. The hydraulic pressure is dominant and can vary between approximately 4 and 5 MPa for depths varying between 400 and 500 m. The swelling pressure of the backfill is designed to be at least 0.1 MPa, but can be up to a couple of MPa depending on backfill material and density. The load is transferred to the base plane in the recess into the tunnel wall.

Uncertainties

The hydraulic pressure depends on the level of the groundwater table, and can be both lower and higher than the physical measure of depth below the surface. This is, however, measured as part of site investigations and, thus, known when the plug design is made.

The swelling pressure of the backfill can be higher than the minimum pressure if higher concentrations of bentonite are placed close to the plug, especially if bentonite pellets are used in the final part of the backfilled tunnel. A maximum increase to a swelling pressure of 3 MPa is considered.

The hydraulic head can instantaneously increases due to blasts in connection with excavation of new disposal tunnels in the repository, however, no more than 0.1 MPa.

9.2.6 Materials – composition and content

Initial value

The retaining wall and the plug are made of reinforced concrete. Retaining wall is made of seven prefabricated reinforced concrete bars. The wall has a volume of about 6 m^3. The estimated amounts of reinforcement and U-links in the wall are: 200 m reinforcement bars with the diameter 25 mm and 200 m with the diameter 16 mm, and in addition 480 m U-links with the diameter 12 mm.

The plug has a total volume of 60–70 m^3. The ballast in the concrete is assumed to be made from rock excavated in the repository. The estimated amounts of reinforcement in the plug are: 6,700 kg reinforcement bars with the diameter 25 mm and 700 kg with the diameter 10 mm. Other components in the plug are contact grouting tubes (type: Fuko) and cooling tubes made of steel. Gaps are formed between the plug and the rock due to shrinkage of the concrete. Therefore the tubes for contact grouting are fixed to the slot surface bearing area. The grout is required when the hydrostatic load is going to be applied. Contact grouting may also improve the hydraulic sealing of the plug.

Both the retaining wall and the abutment and the main body of plug will be made of concrete with low alkali cement. The development of a recipe for the low alkali construction concrete is in progress. An example of a low alkali pH construction concrete is given in Table 6-2. The amount of materials in the plug is estimated based on this information, see Table 9-3.

Table 9-3. Estimated amounts of material in an operational plug.

Concrete components	**Amounts (tonnes per plug)**	
	Retaining wall	**Plug**
Cement	2	18
Silica Fume	0.6	6
Ballast – sand	5.9	52
Ballast (4–5 mm)	9.0	85
SP40	0.05	0.4

Uncertainties

The two key factors in casting a successful plug are: 1) low-pH concrete, and 2) self-compacting properties of the concrete. If this can not be met by a new material the presently used types need to be used. This would mean that the plugs must be retrieved before sealing.

The ballast in the concrete is assumed to be made from rock excavated in the repository. Other types may be used by different reasons, like the wish to use natural sand in order to decrease the amount of cement. This other ballast type may have a different chemistry and impact the over all chemical regime around the plug.

9.2.7 Pore water composition

The pore water composition has presently not be specified.

10 Borehole seals

10.1 General

A number of more or less vertical investigation or surface-based characterisation boreholes are drilled during site investigations in order to obtain e.g. data on the properties of the rock. These boreholes will be sealed, no later than at the closure of the deep repository. In addition, some holes are bored from the repository tunnels during the construction phase meaning that also horizontal and upwards directed holes have to be sealed.

The borehole seals shall prevent short-circuiting of flow of contaminated groundwater from the repository. They should therefore not be more permeable than the undisturbed, surrounding rock. Time-dependent degradation must be accepted but the goal is to find plug materials that maintain their constitution and tightness for a long time. Where the boreholes intersect fracture zones it is meaningless to seal them effectively over this length, while it is important to make the plugs tight in the intervals between the fracture zones. An important sealing criterion is that the seal must be in tight contact with the rock, which can be achieved if the plug material consists of expanding clay that exerts an effective (swelling) pressure on the borehole walls. Time dependent degradation of the plugs must be accepted.

These holes will not intersect deposition holes or tunnels. It is assumed that they are sealed so that the have no impact on the long-term safety.

Sealing reference concept

Seals for boreholes are under development as part of SKB's RD&D programme. The concept presented here is one example of how the investigation boreholes can be sealed. The proposed concept is that highly compacted smectitic clays are used where tight seals are needed and that casting cement-stabilised plugs are applied where the boreholes passes through fracture zones. The design of the tight seals are basically the same as has been used for deep boreholes in the SFR area and extensively tested in the international Stripa Project.

For any hole length one can use plugs consisting of cylindrical pre-compacted clay blocks that are contained in perforated copper tubes that are jointed in conjunction with insertion into the holes. The copper tubes provide mechanical protection against abrasion in the application phase. The clay is preferably rich in the smectite type montmorilllonite. The plugs mature by hydration of the clay cores, which expand and give off clay that migrates through the perforation of the tubes and ultimately embeds them in homogeneous, dense clay.

The uppermost part of the holes will be sealed with material that can sustain the swelling pressure exerted by the clay part and also offer resistance to mechanical impact like intrusion, erosion and glaciations

Procedures in borehole sealing

Three main procedures are required, namely: clearing and stabilization of the boreholes, construction and emplacement of the plugs, and sealing and securing the uppermost parts.

Before sealing, fracture zones and rock fallouts in the holes requires stabilisation for making it possible to emplace the plugs and ensure that the diameter of the hole is constant along the whole borehole length. Grouting will be used for stabilisation and the holes are re-bored thereafter. No estimates of the amount of grout penetrating the fractures in rock are presently available. The holes are then plugged with pre-compacted bentonite blocks.

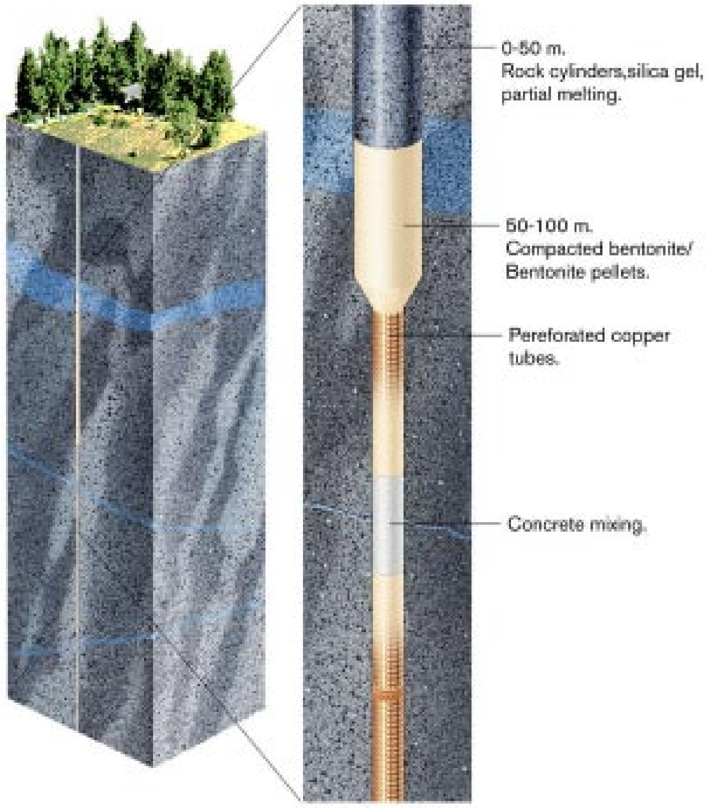


Figure 10-1. *Reference concept for sealing investigation boreholes drilled from the surface.*

10.2 Variables

10.2.1 Overview

The seal geometry in the boreholes is bounded on one end and the sides by the interface towards the rock. The other end of the borehole has either an open interface to the biosphere if the borehole is drilled from the surface or is bounded by the backfill in tunnels if the borehole is drilled from the repository.

The backfill in the boreholes is characterised thermally by its temperature, hydraulically by the hydro variables (pressure and flows), and mechanically by the stress state. The chemical state of the backfill is defined by the composition of the materials and the pore water composition. The variables are defined in Table 10-1.

10.2.2 Geometry

Initial value

The seals geometry is mainly determined by the dimensions of the drilled holes. Characterisation boreholes are either drilled from the surface, surface-based boreholes, or drilled from the tunnels and cavities, tunnel-based boreholes.

The length of surface-based boreholes ranges from a few metres to a couple of kilometres and the diameter will presumably range from 56 to 120 mm. The tunnel-based boreholes are expected to have a length of a few hundred metres and a diameter of 56 to 76 mm. Some boreholes may be more or less horizontal.

Table 10-1. Variables for borehole seals.

Variable	Definition
Geometry	Geometric dimensions for backfill in boreholes. A description of e.g. interfaces towards the geosphere and tunnel backfill. Pore geometry as a function of time and space in backfill in boreholes. The porosity, i.e. the fraction of the volume that is not occupied by solid material is often given.
Backfill materials – composition and content	Chemical composition and content of the backfill in boreholes (including any radionuclides) in time and space. This variable also includes material sorbed to the surface.
Temperature	Temperature as a function of time and space in backfill in boreholes.
Hydro variables (pressures and flows)	Flows and pressures of water and gas as a function of time and space in backfill in boreholes.
Stress state	Stress state as a function of time and space in backfill in boreholes.
Water composition	Composition of the water in backfill in boreholes (including any radionuclides and dissolved gases) in time and space.

The position, direction, length and diameter of each drilled borehole are documented in the SKB Sicada database during site investigation and construction phases. Boreholes drilled prior to the site investigation have been inventoried and documented prior to the site investigation.

The porosity in the clay seal is approximately 0.5% after saturation and homogenisation.

Uncertainties

The final number of boreholes is presently unknown but the position, direction and the geometry (diameter and length) of boreholes at the sites are well documented.

The boreholes are in the ideal case round, but they are deformed by the rock stress into oval shapes, as higher the stresses are and as higher the ratio is between major and minor principal stresses.

The shape may divert quite a lot from the ideal round shape at intersections with fracture zones, and the casting and re-drilling may be difficult to complete with a long-lasting material.

Cave-ins can have occurred in week zones and cleaning before casting and re-drilling can be difficult to do.

10.2.3 Temperature

Initial value

The backfill in the boreholes will be in thermal equilibrium with the undisturbed host rock in the initial state. That value varies with depth and is in average approximately 10–15°C.

Uncertainties

The uncertainty may be around 5°. This is of no importance to the thermal evolution at the site.

10.2.4 Hydro variables (flows and pressure)

Initial value

The rate of water saturation depends on the initial density of the clay, the diameter of the borehole and clay plug, and the chemical composition of the groundwater in the borehole. For a 56 mm borehole in rock with low-electrolyte groundwater under low pressure (< 0.5 MPa) it will take up to 90 days to get a homogeneous clay plug with an average degree of saturation of 95%. In Ca-rich salt groundwater it will only take a couple of weeks. For a 120 mm borehole in rock with low-electrolyte groundwater it will take one year to reach homogeneous conditions and an average degree of saturation of 95%. At water pressures exceeding 5 MPa water head the respective times are less than 50% of the ones given here. The initial rate of homogenization of clay plugs is most important for the placement of borehole plugs.

Both the experiments and the modelling show that clay migrates out through the perforated copper tube to an extent that can make the placement difficult. The difficulties may occur after 48 hours if the borehole contains fresh-water and already after 8 hours if the groundwater has a high salt content with Ca as major cation.

Uncertainties

Water flow, especially in salt groundwater environment, can cause erosion of the bentonite and thereby reduce the swelling properties and the saturated density when full saturation has been reached.

Cement reacts with bentonite and the need for stabilising measures in weak zones can cause the cement to neutralize bentonite and thereby reduce the bentonite's sealing potential.

10.2.5 Stress state

Initial value

Rock stresses down to 1,000 m depth are not expected to create problems with hole shapes and hole stabilities.

Uncertainties

Higher stresses than the generally expected ones have been observed randomly in Sweden by SKB. Stresses have been high enough for creating core disking, i.e. mechanical failure. In boreholes this is an indicator of geometrical deformation of the shape.

Absolute stress measurements have, however, not been made in such horizons because of the feature of accurate stress measurements is to work in un-fractured rock.

10.2.6 Backfill materials – composition and content

Initial value

The content of backfill in a surface-based borehole is determined by its depth and diameter. The applied concept comprises the following materials at different depths:

- On the ground surface, filling of 3 m well compacted till from the site.
- 3–50 m, close fitting rock cylinders pressed down in the precision-drilled (reamed) uppermost part of the hole. The cylinders are from the site. Silica gel is used as mortar.
- 50–60 m, fill of well compacted till from the site. It constitutes a transfer from the effective underlying ductile clay seal to the overlying stiff borehole plug.

- 60–100 m, fill of smectite pellets of bentonite applied and compacted layerwise.
- Below 100 m, highly compacted smectite clay contained in perforated copper tubes (2–4 mm thick walls and degree of perforation is approximately 50%). Tubes are jointed to form a continuous clay column.

Tunnel-based boreholes are filled with highly compacted smectite clay contained in perforated copper tubes that are jointed to form a continuous clay column. These boreholes are plugged with concrete at the tunnel. Short holes drilled down in the repository are not expected to affect the groundwater flow pattern or the engineered barriers and can therefore be sealed with e.g. bentonite pellets.

Fracture zones and rock fallouts in the holes requires stabilisation for making it possible to emplace the plugs and ensure that the diameter of the hole is constant along the whole borehole length. Grouting will be used for stabilisation and the holes are re-bored thereafter. No estimates of the amount of stabilising concrete and grout penetrating the fractures in rock are presently available. The concrete may be of a low pH type.

The composition of the bentonite is assumed to be the same as in the buffer, see Sections 5.2.10 and 5.2.11. Clay powder is used for preparing the bentonite blocks. A compaction pressure of 50 to 150 MPa gives dry densities on the order of 1,600 to 2,000 kg/m^3 (2,008 to 2,260 kg/m^3 after water saturation under confined conditions) if the grain size distribution is suitable. Too small grains make it difficult for air enclosed in the voids to dissipate in the compaction process, a suitable size distribution being shown in Table 10-2.

Uncertainties

Long boreholes offer difficulties with respect to straightness. Curved holes, particularly with several bends, may cause difficulties in bringing in long, stiff plugs. It is believed that the friction mobilized in the insertion of long plugs can require high axial forces and that an unshielded clay plug can break and disintegrate when forced into a borehole.

The described composition of the borehole plugs from the ground surface and downwards will make it impossible to locate the borehole for unauthorized people and to reach into it without access to very effective excavation tools. Glaciations are not expected to erode more than 50 m at maximum, which means that the moraine layer (at 50–60 m depth) in the hole may be exposed but not the clay below it. The clays below this level provide the essential borehole seal.

Table 10-2. Suitable grain size distribution for achieving high block densities.

Fractions, mm	Percentage of grain size representing each fraction
2–8	20.0
1–2	20.4
0.1–1	42.4
< 0.1	17.2
Total	100

10.2.7 Water composition

Initial value

Pore water composition in bentonite has been discussed and described in many reports, articles and previous safety reports. In general, the pore water composition is mainly determined by:

- The charge compensating cations in the montmorillonite.
- Equilibrium with the minerals in the bentonite.
- Ions added with solution.
- Total amount of water.

See also Section 7.2.10.

The ground water composition varies with the depth below the ground surface, and has an increasing salt gradient with depth from a certain depth below the sea water level.

Uncertainties

The ion equilibrium between charge compensating ions and all other ions in the system is not fully understood.

11 References

Andersson C-G, Eriksson P, Westman M, Emilsson G, 2004. Status report, canister fabrication. SKB TR-04-23, Svensk Kärnbränslehantering AB.

Bjurström H, Bruce A, 1997. (In Swedish.) Temperaturer i en kapsel enligt TR-95-02, en första uppskattning. SKB Inkapsling PPM 97-3420-28, Svensk Kärnbränslehantering AB.

Bjurström H, Bruce A, 1998. (In Swedish.) Temperaturer i en kapsel enligt TR-95-02, etapp 2. SKB Inkapsling PPM 98-3420-30, Svensk Kärnbränslehantering AB.

Bradbury M H, Baeyens B, 2002. Porewater chemistry in compacted re-saturated MX-80 bentonite: Physico-chemical characterisation and geochemical modelling, PSI Bericht Nr. 02-10, Nagra NTB 01-08. ISSN 1019-0643.

Brantberger M, Zetterqvist A, Arnbjerg-Nielsen T, Olsson T, Outters N, Syrjänen P, 2006. Final repository for spent nuclear fuel. Underground design Forsmark, Layout D1. SKB R-06-34, Svensk Kärnbränslehantering AB.

Bäckblom G, Christiansson R, Hedin A, Norman F, Lagerstedt L, 2003. (In Swedish.) Utredning rörande tillträdesvägar till djupförvarets deponeringsområden. Schakt eller ramp? SKB R-03-11, Svensk Kärnbränslehantering AB.

Cau dit Coumes C, Codina M, Bourbon X, Leclercq S, Courtois S, 2005. Formulating a low-alkalinity, high-resistance and low-heat concrete for radioactive waste repositories. Proceedings of 2nd low-pH workshop. Madrid, June 15–16, 2005 Enresa, SKB and the ESDRED-project.

Eriksen T E, Eklund U-B, Werme L, Jordi B, 1995. Dissolution of irradiated fuel: a radiolytic mass balance study. J. Nucl. Mater. Vol. 227, pp. 76–82.

Hedin A, 1997. Spent nuclear fuel – how dangerous is it? A report from the project "Description of risk" SKB TR 97-13, Svensk Kärnbränslehantering AB.

Håkansson R, 1996. (In Swedish.). Beräkning av nuklidinnehåll, resteffekt, aktivitet samt doshastighet för utbränt kärnbränsle. NR-96/079, Studsvik Nuclear AB, Nyköping.

Håkansson R, 2000. (In Swedish.) Beräkning av nuklidinnehåll, resteffekt, aktivitet samt doshastighet för utbränt kärnbränsle. SKB R-99-74, Svensk Kärnbränslehantering AB.

Janson T, Magnusson J, Bergvall M, Olsson R, Cuisiat F, Skurtveit E, Grimstad E, 2006. Final repository for spent nuclear fuel. Underground design Laxemar, Layout D1. SKB R-06-36, Svensk Kärnbränslehantering AB.

Johannesson L-E, Gunnarsson D, Sandén T, Börgesson L, Karlzen R, 2004. Äspö Hard Rock Laboratory. Prototype repository. Installation of buffer, canisters, backfill, plug and instruments in Section II. SKB IPR-04-13, Svensk Kärnbränslehantering AB.

Johnson L H, Tait C, 1997. Release of segregated nuclides from spent fuel. SKB TR 97-18, Svensk Kärnbränslehantering AB.

Karnland O, Olsson S, Nilsson U, Sellin P, 2006. Mineralogy and sealing properties of various bentonites and smectite-rich clay materials. SKB TR-06-30, Svensk Kärnbränslehantering AB.

Leggatt R H, 1995. Measurements of residual stesses in copper canisters. SKB Inkapsling PPM 96-3420-14, Svensk Kärnbränslehantering AB.

Lindgren L-E, Häggblad Å, Josefson L, Karlsson L, 1999. Thermo-mechanical FE-analysis of residual stresses and stress redistribution in butt welding of a copper canister for spent nuclear fuel. Presented at the Int Conf on Structural Mechanics in Reactor Technology. SmiRT-15, Seoul, Korea, Aug 15–20.

Lundgren K, 1997. (In Swedish.) Kontroll av strålskärmsberäkningar för kopparkapsel. ALARA Engineering Rapport 97-0028R (rev 1).

Lundgren K, 2004. Final disposal of fuel – electron radiation outside copper canister. SKB TR-04-06, Svensk Kärnbränslehantering AB.

Möller G, Petersons N, Samuelsson P, 1982. (In Swedish.) Betonghandbok. Material. Svensk Byggtjänst.

Pusch R, 2002. The Buffer and Backfill Handbook. Part 1: Definitions, basic relationships and laboratory methods. SKB TR-02-20, Svensk Kärnbränslehantering AB.

Sievänen U, Syrjänen P, Ranta-Aho S, 2004. Injection grout for deep repositories. Low-pH cementitious grout for larger fractures. Field testing in Finland, Pilot Tests. Posiva Working Report 2004-47. Posiva Oy.

SKB, 1999. Deep repository for spent nuclear fuel. SR-97 – Post-closure safety. SKB TR-01-30, Svensk Kärnbränslehantering AB.

SKB, 2002. (In Swedish.) Djupförvar för använt kärnbränsle. Anläggningsbeskrivning – Layout E Spiralramp med ett driftområde. SKB R-02-18, Svensk Kärnbränslehantering AB.

SKB, 2004a. RD&D-Programme 2004. Programme for research, development and demonstration of methods for the management and disposal of nuclear waste, including social science research. SKB TR-04-21, Svensk Kärnbränslehantering AB.

SKB, 2004b. Deep repository. Underground design premises. Edition D1/1. SKB R-04-60, Svensk Kärnbränslehantering AB.

SKB, 2005a. (In Swedish.) Plan 2005. Kostnader för kärnkraftens radioaktiva restprodukter. Svensk Kärnbränslehantering AB.

SKB, 2005b. Preliminary site description. Forsmark area – version 1.2. Updated 2005-11-09. SKB R-05-18, Svensk Kärnbränslehantering AB.

SKB, 2006a. Kapsel för använt kärnbränsle. Tillverkning av kapselkomponenter. SKB R-06-03, Svensk Kärnbränslehantering AB.

SKB, 2006b. Kapsel för använt kärnbränsle. Svetsning vid tillverkning och förslutning. SKB R-06-04, Svensk Kärnbränslehantering AB.

SKB, 2006c. Kapsel för använt kärnbränsle. Oförstörande provning av kapselkomponenter. SKB R-06-05, Svensk Kärnbränslehantering AB.

SKB, 2006d. Kapsel för använt kärnbränsle. Oförstörande provning av svetsar. SKB R-06-06, Svensk Kärnbränslehantering AB.

SKB, 2006e. Kapsel för använt kärnbränsle. Program för kvalificering av tillverkning och förslutning. SKB R-06-07, Svensk Kärnbränslehantering AB.

SKB, 2006f. Buffer and backfill process report for the safety assessment SR-Can. SKB TR-06-18, Svensk Kärnbränslehantering AB.

SKB, 2006g. Data report for the safety assessment SR-Can. SKB TR-06-25, Svensk Kärnbränslehantering AB.

SKB, 2006h. Preliminary Site Description. Laxemar area version 1.2. SKB R-06-10, Svensk kärnbränslehantering AB.

SKBF/KBS, 1983. Final storage of spent nuclear fuel – KBS-3. Svensk Kärnbränslehantering AB/avd KBS.

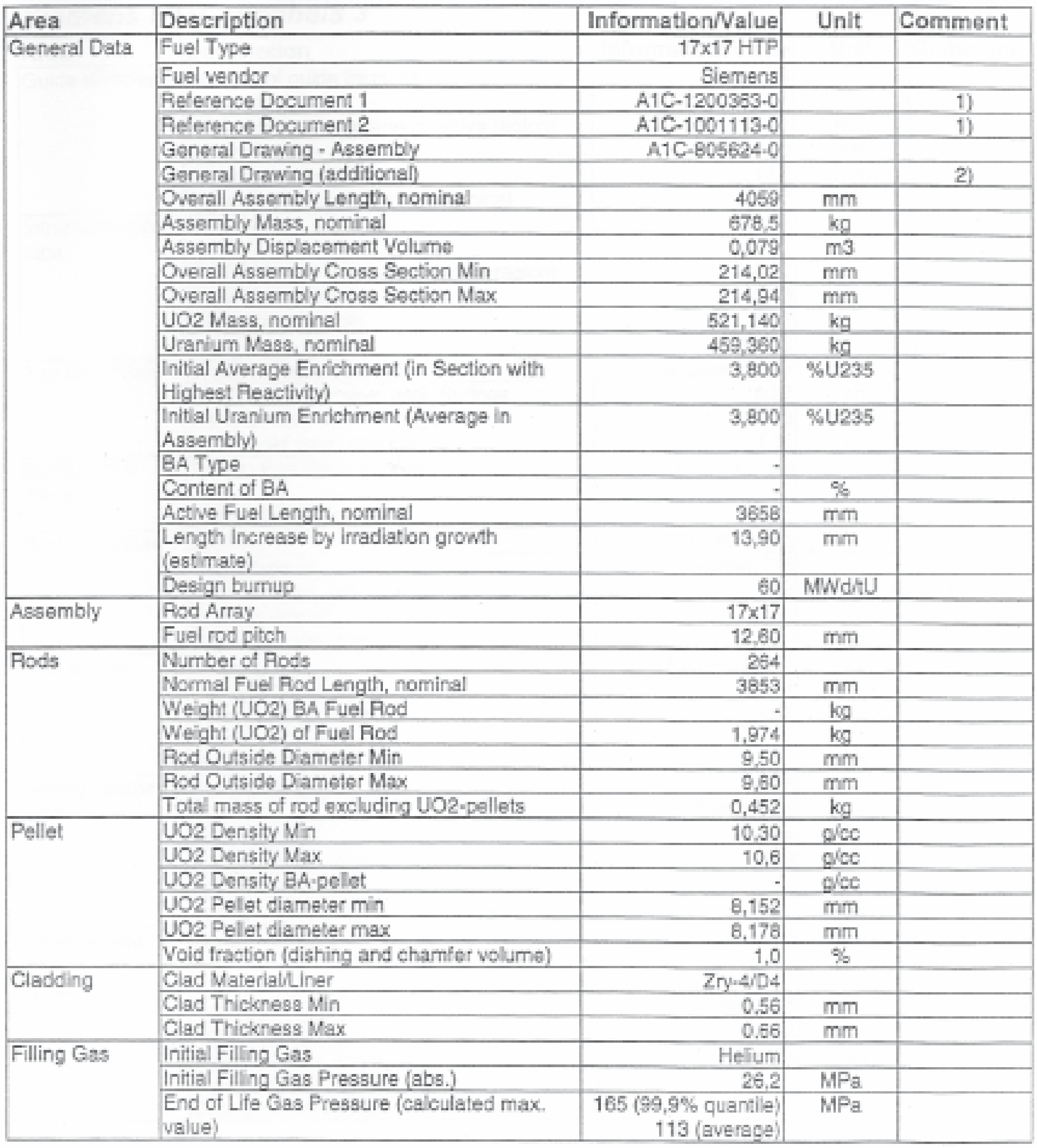
Stroes-Gascoyne S, 1996. Measurements of instant-release source terms for ^{137}Cs, ^{90}Sr, ^{99}Tc, ^{129}I and ^{14}C in used CANDU fuels, J. Nucl. Mater. 238, 265–277.

Werme L O, Johnson L H, Oversby V M, King F, Spahiu K, Grambow B, Shoesmith D W, 2004. Spent fuel performance under repository conditions: A model for use in SR-Can. SKB TR-04-19, Svensk Kärnbränslehantering AB.

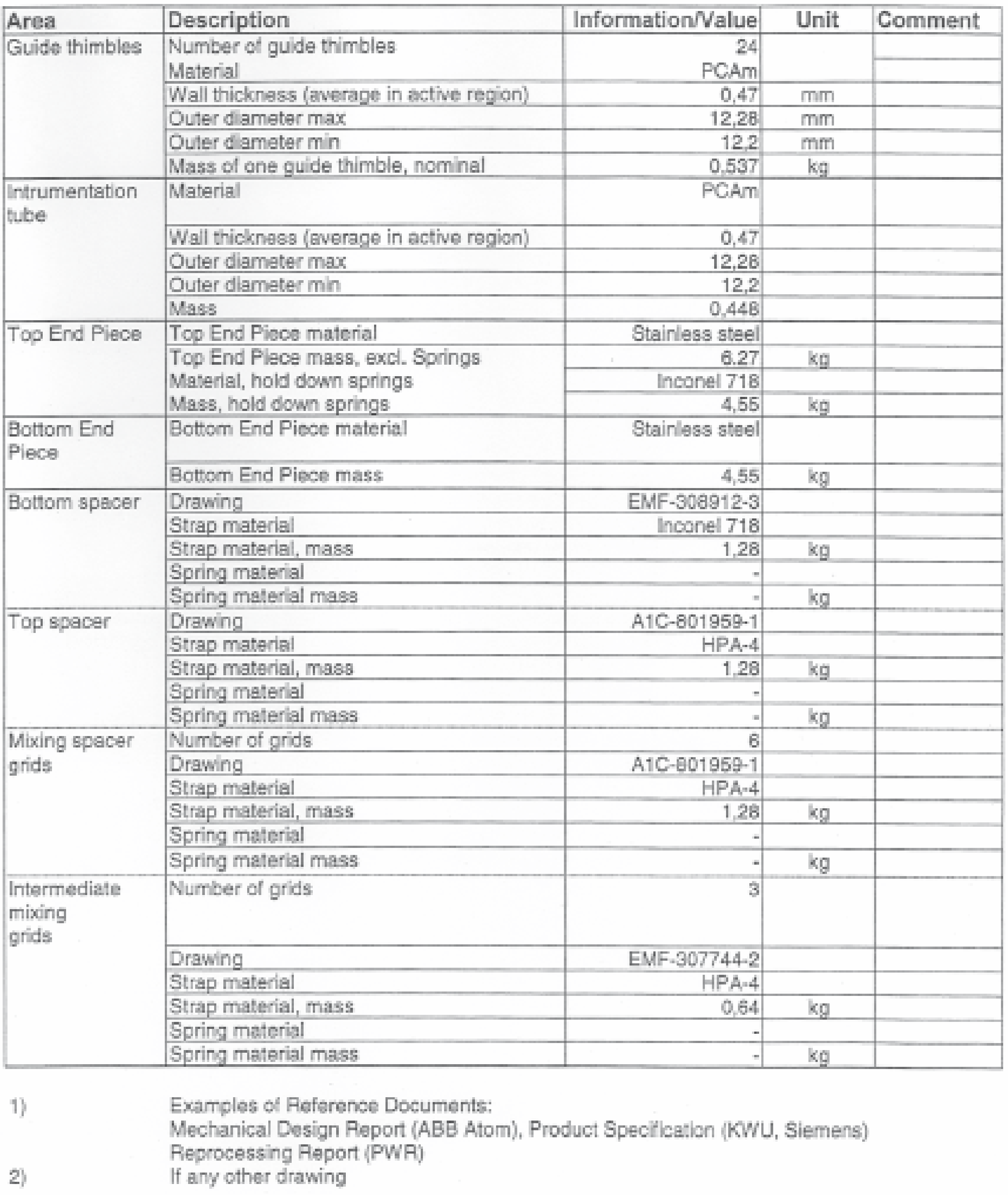
Appendix 1

Data sheets – reference fuels

Table 1-1. Data for the PWR reference fuel.



Area	Description	Information/Value	Unit	Comment
General Data	Fuel Type	17x17 HTP		
	Fuel vendor	Siemens		
	Reference Document 1	A1C-1200363-0		1)
	Reference Document 2	A1C-1001113-0		1)
	General Drawing - Assembly	A1C-805624-0		
	General Drawing (additional)			2)
	Overall Assembly Length, nominal	4059	mm	
	Assembly Mass, nominal	678,5	kg	
	Assembly Displacement Volume	0,079	m3	
	Overall Assembly Cross Section Min	214,02	mm	
	Overall Assembly Cross Section Max	214,94	mm	
	UO2 Mass, nominal	521,140	kg	
	Uranium Mass, nominal	459,360	kg	
	Initial Average Enrichment (in Section with Highest Reactivity)	3,800	%U235	
	Initial Uranium Enrichment (Average in Assembly)	3,800	%U235	
	BA Type	-		
	Content of BA	-	%	
	Active Fuel Length, nominal	3658	mm	
	Length Increase by irradiation growth (estimate)	13,90	mm	
	Design burnup	60	MWd/tU	
Assembly	Rod Array	17x17		
	Fuel rod pitch	12,60	mm	
Rods	Number of Rods	264		
	Normal Fuel Rod Length, nominal	3853	mm	
	Weight (UO2) BA Fuel Rod	-	kg	
	Weight (UO2) of Fuel Rod	1,974	kg	
	Rod Outside Diameter Min	9,50	mm	
	Rod Outside Diameter Max	9,60	mm	
	Total mass of rod excluding UO2-pellets	0,452	kg	
Pellet	UO2 Density Min	10,30	g/cc	
	UO2 Density Max	10,6	g/cc	
	UO2 Density BA-pellet	-	g/cc	
	UO2 Pellet diameter min	8,152	mm	
	UO2 Pellet diameter max	8,178	mm	
	Void fraction (dishing and chamfer volume)	1,0	%	
Cladding	Clad Material/Liner	Zry-4/D4		
	Clad Thickness Min	0,56	mm	
	Clad Thickness Max	0,66	mm	
Filling Gas	Initial Filling Gas	Helium		
	Initial Filling Gas Pressure (abs.)	26,2	MPa	
	End of Life Gas Pressure (calculated max. value)	165 (99,9% quantile) 113 (average)	MPa	



Area	Description	Information/Value	Unit	Comment
Guide thimbles	Number of guide thimbles	24		
	Material	PCAm		
	Wall thickness (average in active region)	0,47	mm	
	Outer diameter max	12,28	mm	
	Outer diameter min	12,2	mm	
	Mass of one guide thimble, nominal	0,537	kg	
Intrumentation tube	Material	PCAm		
	Wall thickness (average in active region)	0,47		
	Outer diameter max	12,28		
	Outer diameter min	12,2		
	Mass	0,448		
Top End Piece	Top End Piece material	Stainless steel		
	Top End Piece mass, excl. Springs	6.27	kg	
	Material, hold down springs	Inconel 718		
	Mass, hold down springs	4,55	kg	
Bottom End Piece	Bottom End Piece material	Stainless steel		
	Bottom End Piece mass	4,55	kg	
Bottom spacer	Drawing	EMF-308912-3		
	Strap material	Inconel 718		
	Strap material, mass	1,28	kg	
	Spring material	-		
	Spring material mass	-	kg	
Top spacer	Drawing	A1C-801959-1		
	Strap material	HPA-4		
	Strap material, mass	1,28	kg	
	Spring material	-		
	Spring material mass	-	kg	
Mixing spacer grids	Number of grids	6		
	Drawing	A1C-801959-1		
	Strap material	HPA-4		
	Strap material, mass	1,28	kg	
	Spring material	-		
	Spring material mass	-	kg	
Intermediate mixing grids	Number of grids	3		
	Drawing	EMF-307744-2		
	Strap material	HPA-4		
	Strap material, mass	0,64	kg	
	Spring material	-		
	Spring material mass	-	kg	

1) Examples of Reference Documents:
Mechanical Design Report (ABB Atom), Product Specification (KWU, Siemens)
Reprocessing Report (PWR)

2) If any other drawing

Table 1-2. Data for the BWR reference fuel.

Area	Description	Unit	Value
	Fuel Type		SVEA 96
General Data	Fabricate		ABB ATOM
	Licensing date CLAB		1989-07-07
	Licensing date Transport Container		1989-07-07
	Reference Document 1		G6264.8
	Reference Document 2		C-264.13
	General Drawing – Assembly		AA273730
	General Drawing – Box		AA273791
	General Drawing		AA273728
	Overall Assembly Length – Without Fuel Box	mm	4,042.1
	Overall Assembly Length – With Fuel Box	mm	4,422.00
	Assembly Mass (Without Fuel Box)	kg	243.20
	Assembly Displacement Volume	m^3	0.03
	End Zone Bottom Length	mm	56
	End Zone Top Length	mm	273.5
	Overall Assembly Cross Section Min	mm	140.20
	Overall Assembly Cross Section Max	mm	153.00
	UO2 Mass	kg	195
	Uranium Mass	kg	171
	Initial Enrichment (Pellet Enrichment – Maximum)	%U235	
	Initial Average Enrichment (in Section with Highest Reactivity)	%U235	3.461
	Initial Uranium Enrichment (Average in Assembly)	%U235	3.27
	BA Type		Gd203
	Content of BA	%	4
	Active Fuel Length	mm	3,710
	Irradiation Length Increase	mm	15
	Design Burnup	MWd/tU	43,000
Assembly	Rod Array		4*(5*5)
	No of Sub-assemblies		4
	Weight of Sub-assembly	kg	60.8
	Rod Pitch – Minimum	mm	12.7
	Rod Pitch – Maximum	mm	

Area	Description	Unit	Value
Rods	Number of Rods – Total		96
	Number of Fuel Rods		96
	Normal Fuel Rod Length		
	Supporting Fuel Rod Length	mm	4,041
	Spacer Rod Length	mm	4,004.5
	Number of Part Length Rods		
	Length of Part Length Rod	mm	
	Weight (UO2) BA Fuel Rod	kg	2
	Weight (UO2) of Fuel Rod	kg	2.03
	Rod Outside Diameter Min	mm	9.66
	Rod Outside Diameter Max	mm	9.58
	Zr Weight Supporting Rod	kg	0.49
	Zr Weight – Normal Rod	kg	0.47
	Zr Weight – Spacer Rod	kg	0.48
Pellet	UO2 Density Max	g/cc	10.62
	UO2 Density Min	g/cc	10.42
	UO2 Density BA-pellet	g/cc	10.52
	UO2 Pellet Diameter Max	mm	8.203
	UO2 Pellet Diameter Min	mm	8.177
Area	Description	Unit	Value
	Fuel Type		SVEA 96
Cladding	Clad Material/Liner		Zr2
	Clad Thickness Max	mm	0.63
	Clad Thickness Min	mm	0.58
Filling Gas	Initial Filling Gas		He
	Initial Filling Gas Pressure (abs.)	MPa	0.4
	End of Life Gas Pressure	MPa	
Water Channel	Channel Material		
Water	Water Channel Clad Thickness	mm	
	Water Channel Size Max	mm	
	Water Channel Size Min	mm	
Water Rod	No of Water Rods		
	Water Rod Cladding Thickness	mm	
	Water Rod Material		
	Water Rod Outside Diam	mm	
Water Cross	Water Cross Thickness Max	mm	0.8
	Water Cross Thickness Min	mm	
Box	Box Material		Zr2
	Weight of Box	kg	27
	Box Inner Measures	mm	137.4
	Box Wall Thickness	mm	1.1
	Box Bottom Piece Material		SS2352
	Box Zr Weight	kg	27

Area	Description	Unit	Value
Handle	Handle Material		SS2352
	Handle Weight	kg	2.4
Top Plate	Top Plate Material		SS2352
	Top Plate Weight		0.13
Spacers	Number of Spacers in Active Zone		7
	Drawing (Spacers)		
	Axial partition of Spacers		568
	Spacer Thickness	mm	
	Spacer Type 1, Material 1		AMS5542
	Weight of the Above Material	kg	0.23
	Spacer Type 1, Material 2		
	Weight of the Above Material	kg	
	Spacer Type 1, Material 3		
	Weight of the Above Material	kg	
	Spacer Type 2, Material 1		
	Weight of the Above Material	kg	
	Spacer Type 2, Material 2		
	Weight of the Above Material	kg	
	Spacer Type 2, Material 3		
	Weight of the Above Material	kg	
	Spacer Type 3, Material 1		
	Weight of the Above Material	kg	
	Spacer Type 3, Material 2		
	Weight of the Above Material	kg	
	Spacer Type 3, Material 3		
	Weight of the Above Material	kg	
Bottom Plate	Bottom Plate Material		SS2352
	Bottom Plate Weight	kg	0.4

ISSN 1404-0344
CM Digitaltryck AB, Bromma, 2006