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Interim initial state report for the safety assessment SR-Can

Svensk Kärnbränslehantering AB

July 2004

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Preface

This report describes the initial state of the fuel and the engineered parts of the repository for the interim reporting of the safety assessment SR-Can. The report has been compiled and edited by Karin Pers, Kemakta Konsult AB.

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Stockholm, August 2004

Allan Hedin

Project leader, SR-Can

Summary

A thorough description of the initial state of the engineered parts of the repository system is one of the main bases for the SR-Can safety assessment. The initial state refers to the state at the time of deposition for the spent fuel and the engineered barriers and the natural, undisturbed state at the time of beginning of excavation for the repository for the geosphere and the biosphere.

The initial state of the spent fuel and 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 need to be described in order to adequately discuss and handle initial states outside the allowed limits in the safety assessment. The initial state of the spent fuel and engineered parts is compiled in this report.

The repository system is based on the KBS-3 method, where 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.

For the purpose of the safety assessment the engineered portion of the repository system has been divided into a number of consecutive barriers or sub-systems. Homogeneous components facilitate both characterisation of a component and the structuring and handling of processes in 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 more peripheral components.

The initial state of each sub-system is described by a set of 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 beginning of 2003, approximately 5700 tonnes of spent fuel have been generated /SKB, 2003/. With an operating time of 40 years for all reactors, except for Barsebäck 1 which was taken out of operation during 1999, the total quantity of spent fuel can be estimated at 9500 tonnes /SKB, 2003/.

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 7200 tonnes and the quantity of PWR fuel at 2300 tonnes /SKB, 2003/. In addition, 23 tonnes of MOX fuel and 20 tonnes of fuel from the reactor in Ågesta will be deposited. The fuel burn-up may vary from 15 MWd/kgU up to 60 MWd/kg /SKB, 2001/.

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. 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 marginally regarding radionuclide content. Deviations in inventory and deviating or damaged fuel are not considered in the SR-Can interim reporting but will be handled in the final reporting of SR-Can.

The canister insert is sealed at atmospheric pressure (dry air or noble 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 and thus presumes that no more than one Zircaloy cladding tube is defective. For the safety assessment, it can however not be ruled out that no more than one tube is defective. For the safety assessment, it can however not be ruled out that more than one tube is defective.

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 5 cm 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 deposited in one canister is limited to 1700 W, to fulfil temperature requirements at the canister surface in the deposition hole. A total of about 4500 canisters will be produced according to current estimates.

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 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. The reference canister is foreseen to be fabricated with a seamless tube. Lids and bottoms of copper are machined to the desired dimensions from hot forged blanks. 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 can be done either by friction-stir welding (FSW) or by electron-beam welding (EBW). The aim is to select one welding method during 2005. Methods for non-destructive testing (NDT) of the canisters and welds are being developed. Examples of applied methods for this are radiographic and ultrasonic testing.

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 copper shell's lid is then attached by welding, and the integrity of the weld is verified by NDT. Uncertainties in the initial geometry of the canister primarily concern canister integrity. The canisters are to be fabricated, sealed and inspected to guarantee that no more than 0.1 percent of the finished canisters will contain discontinuities that are greater than what is permitted by the acceptance criteria. The probability of a defect is greatest in the lid weld, since the possibilities of inspection and testing are better for the bottom weld.

Buffer

In the deposition holes, the copper canister is surrounded by a buffer of clay. The buffer is deposited as bentonite blocks and rings. Each bentonite unit is about 500 mm high and has a diameter of 1690 mm. The thickness of the rings is 315 mm. One block is placed below the canister, nine rings surround the canister and three blocks are placed above the canister. The blocks placed immediately below and above the canister must be processed so as to fit the canister geometry properly.

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 bentonite consists mainly of the smectite mineral montmorillonite with the characteristic property that it swells in contact with water.

There are primarily two methods available for fabrication of bentonite blocks and rings; unaxial pressing and isostatic pressing. Objects higher than 0.5–1 m cannot be easily produced by unaxial pressing and the development of isostatic pressing is therefore important, since no equipment to fabricate full size buffer components with isostatic pressing is available in Sweden today. Fabrication of the blocks and rings by isostatic pressing requires that the objects are machined to the tolerances specified. 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 aspect 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 1950–2050 kg/m^3. The bulk density is dependent on the slots left for technical reasons between the canister and buffer and between buffer and rock. The slot between the canister tube and the buffer is 5 mm and the slot along the circumferential boundary between the buffer and the rock is 30 mm. The slots are left filled with air.

The 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 probably be documented with a photograph of the canister in its final position before the remaining bentonite blocks are emplaced. 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 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 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.

Bottom plate in deposition holes

The bottom of the deposition hole is levelled off with a cast concrete base plate. The bottom plate serves as a rigid 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 bottom plate will be adapted to the roughness of the rock and is about 5 cm at the thinnest part and 10 cm as a maximum. The plate is cast of concrete with low pH cement. The development of suitable cement is in progress, but a final recipe is presently not available. A copper plate, a few millimetres thick, is placed on the concrete surface to protect the bentonite from being wetted with ground water penetrating the concrete plate. A periphery slot is left between the concrete bottom 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 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. 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 analysed in SR-Can. The excavation technique will have implications on the dimensions and shape of the deposition tunnels. The cross section in a drill and blast deposition tunnel is a square with an arched roof, whereas the cross section in a mechanically excavated tunnel is circular.

Two different backfill concepts are analysed. One is an in situ compacted mixture of crushed rock and bentonite of the same type as in the buffer and the other comprises pre-compacted blocks of Friedland clay. The upper metre of the deposition holes will be filled with the mixture in the first concept and with bentonite blocks with buffer quality in the second concept. The mixing concept will have a final clay fraction density of around 1600 kg/m^3 when water saturated and the natural clay concept will have a saturated.

The manufacturing of the backfill material will take place in a production facility close to the deep repository. Quality control of the composition of the material will take place at three stages: the clay and the ballast 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 of the mixture 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 addition, the tunnels will be cleaned with highly pressurised water.

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.

Plugs

Each backfilled deposition tunnel needs to be sealed awaiting the backfilling of the main tunnel. 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 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.

The plugs will be left in the repository at its closure, but they have no long-term safety functions.

Borehole seals

A number of more or less vertical investigation or surface-based 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 deep 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 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 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 moraine (0–3 m), close-fitting rock cylinders from the site (3–50 m), compacted moraine (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 plugged with concrete at the tunnel.

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1 Introduction

Nuclear waste in Sweden is handled by the Swedish Nuclear Fuel and Waste Management Co, SKB. Several decades of research and development has led SKB to put forward the KBS-3 method for the final stage of the 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 9000 tonnes of spent nuclear fuel is forecasted to arise from the Swedish nuclear power program, corresponding to roughly 4500 canisters in a KBS 3 repository.

Two principal remaining tasks in the program are to locate, build and operate i) the deep repository and ii) an encapsulation plant in which the spent fuel will be emplaced in canisters to be deposited in the deep repository. The two applications foreseen in the current stage of SKB's program for spent nuclear fuel will each require a report on long-term safety for the deep repository. This is an obvious requirement for the application to build the repository. Also the application to build the encapsulation plant will require such a report since, in that application, it must be demonstrated that a repository with the sealed canisters to be delivered from the encapsulation plant will meet the requirements on long-term safety set up by Swedish authorities.

Two safety reports will thus be produced within the next few years; one for the application to build an encapsulation plant and one for the application to build the repository. They are referred to as SR-Can and SR-Site, respectively. SR-Can will be based on site data from the initial site investigation phase and SR-Site on data from the complete site investigation.

1.1 SR-Can safety assessment

As mentioned, SR-Can will be used for SKB's application to build an Encapsulation Plant. The purposes of the safety assessment SR-Can are the following:

1. The primary purpose of SR-Can is to assess the safety of a KBS 3 repository at Forsmark and Simpevarp with canisters according to the application to build the encapsulation plant.
2. Secondarily, SR-Can should provide feedback to design development, to SKB's R&D programme, to further site investigations and to future safety assessment projects.

The main purpose of the Interim Report of SR-Can, to which this Interim Initial State Report is a supporting document, is to demonstrate the methodology to be used in the assessment, so that this can be reviewed before it is used for the applications.

The structure of this Interim Initial State Report, covering the engineered parts of the repository, follows that envisaged for the final report.

1.2 Initial state

A thorough description of the initial state of the engineered parts of the repository system is one of the main bases for the safety assessment.

The initial state refers to the state at the time of deposition for the spent fuel and the engineered barriers and the natural, undisturbed state at the time of beginning of excavation for the repository for the geosphere and the biosphere. The natural system will thus, at least in some aspects, be followed from the time of beginning of excavation in the safety assessment.

The initial state of the spent fuel and 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 need to be described in order to adequately discuss and handle initial states outside the allowed limits in the safety assessment. 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, which is not covered in this report, must be 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 /SKB, 2004a/.

1.2.1 Reference initial state for spent fuel and engineered barriers

The reference initial state of the engineered barriers is largely obtained from the design specifications with tolerances including allowed tolerances or deviations. Also the manufacturing, excavation and control methods need to be described in order to adequately discuss and handled initial states outside the allowed limits in the safety assessment. The reference initial state thus does not reflect an ideal repository.

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 deep repository program, such procedures have reached a varying degree of maturity. This means that the tolerances will be more or less well specified for different aspects of the EBS initial state. For e.g. the crucial quality of the canister seals, the intention for SR-Can is to base the tolerances on test statistics from 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. This is e.g. 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 a derivation of a measured tolerance.

The approach managing the uncertainties represented by the tolerances including the possibility of initial state values outside the tolerances and the use of safety assessment results in the further design work, is developed in conjunction with the selection of scenarios.

Format for initial state descriptions

The initial state of each barrier or sub-system is described by a set of variables, selected to allow an adequate description of the long-term evolution of the component in question in the safety assessment.

2 System description

2.1 Introduction

The repository system is based on the KBS-3 method, where copper canisters with a cast iron insert containing spent nuclear fuel are surrounded by bentontie clay and deposited at approximately 500 m depth in saturated granitic rock, see Figure 2-1.

For the purpose of the safety assessment the engineered portion of the repository system has been divided into a number of consecutive barriers or sub-systems:

- The spent fuel that also includes the cavity in the canister.
- The cast iron insert and the copper canister.
- The buffer.
- The bottom plate in the deposition holes.
- The deposition tunnel with its backfill material.
- Other repository cavities with their backfill materials.
- 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. Homogeneous components facilitate both characterisation of a component and the structuring and handling of processes in 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 more peripheral components. The components are briefly described below.

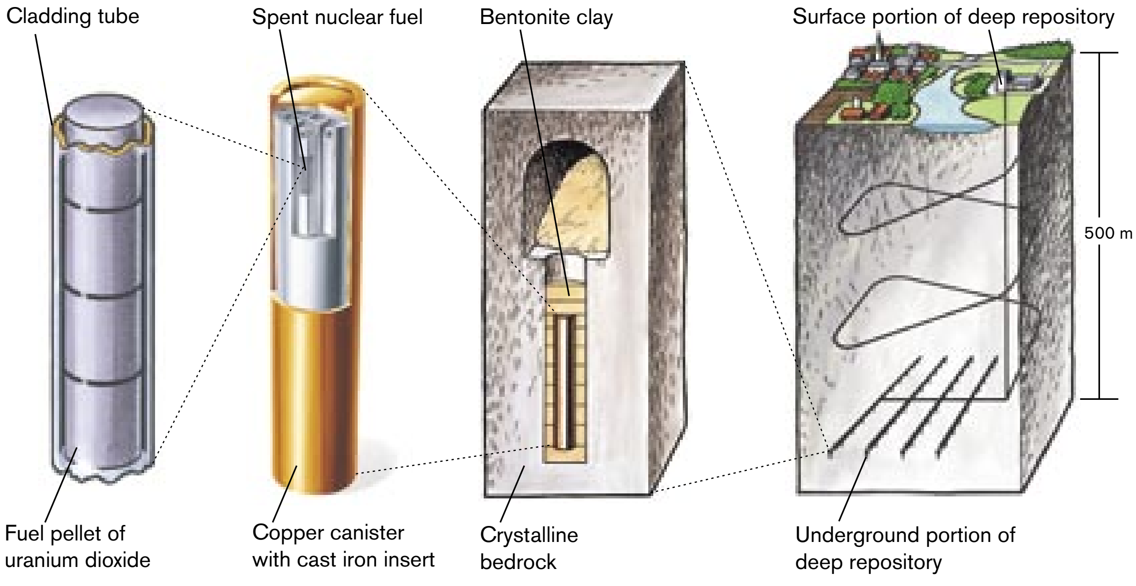

Figure 2-1. The KBS-3 method for storage of spent nuclear fuel.

2.2 Overview of the deep repository for spent fuel

The repository design is based on the KBS-3 system with encapsulation of the spent fuel in corrosion-resistant canister that are surrounded by a clay buffer and deposited in crystalline bed rock. The canisters are deposited in a system of deposition tunnels where the deposition holes have been bored in the floor of the tunnels.

The facility design with rock caverns, tunnels, deposition positions etc in the deep repository for spent fuel is based on the design presented in the KBS-3 report /SKBF/KBS, 1983/ which has been detailed and developed. The deposition tunnels are linked by tunnels for transport, communication and ventilation.

2.2.1 Site specific repository layout

Based on the design specifications of a KBS-3 repository and the site descriptive model 1.1 for Forsmark /SKB, 2004a/ a site specific layout at the Forsmark site has been developed.

The recommendation for the generic 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 the generic arrangement.

Based on site descriptive model version 1.1 for Forsmark and the reference layout a site specific layout for the underground facility was developed. When information was missing in version 1.1 older material (version 0) was used.

In principle the analyses followed the model described in the design premises /SKB, 2004b/, but all steps in the model were not performed and instead a number of assumptions were made in order to simplify the work and shorten the time schedule:

- As in the reference case the deposition tunnels should be separated by 40 metres and the spacing between the deposition holes should be 6 metres.
- The length of the deposition tunnels could vary between 100 and 300 m, compared with 265 in the generic arrangement.
- The deep repository should be located in the northern part of domain 29.
- All fracture zones were assumed to be vertical.
- The operational area should be placed at the area used for temporary housing for service personnel.
- The underground facility should be placed 500 m below ground.

Rock mechanical analyses according to the design premises showed that a large portion of the deposition holes had to be abandoned because of rock burst when locating the underground facility at a depth of 500 m. An alternative layout for the underground facility was developed for a depth of 400 m below ground.

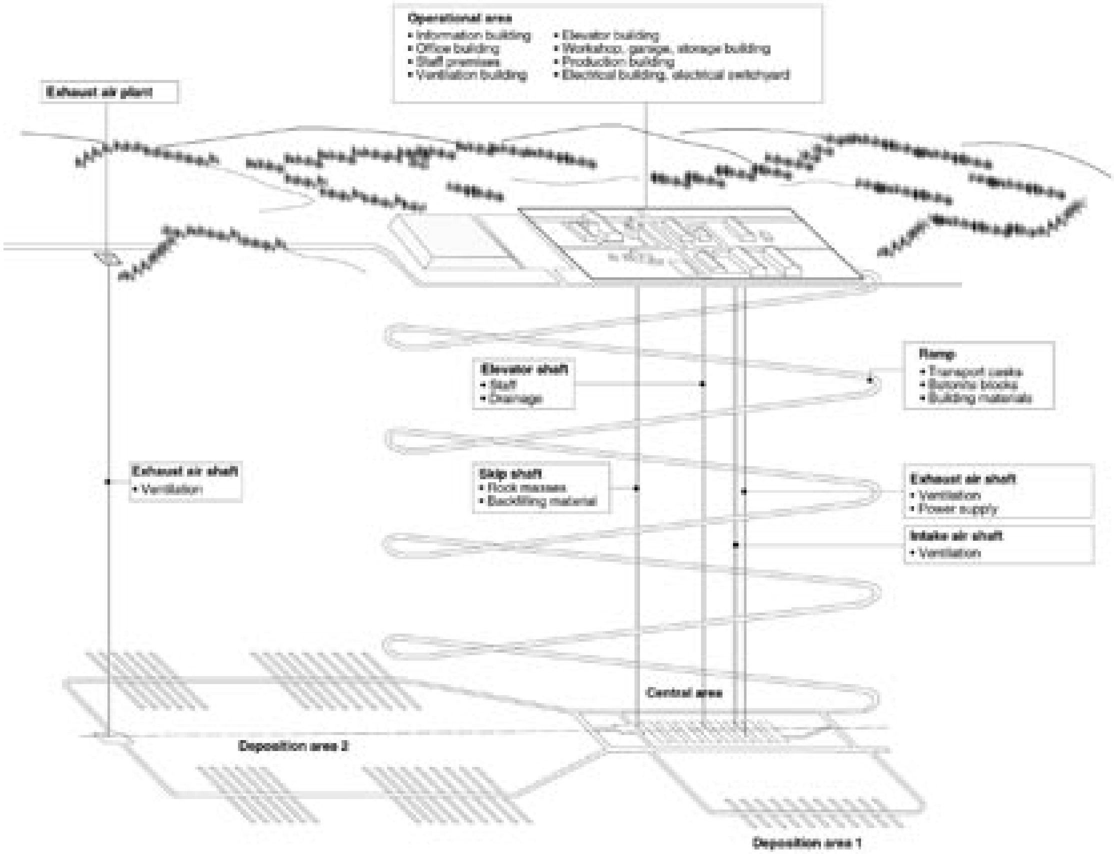

Figure 2-2. *Generic arrangement for the reference repository.*

Another important conclusion from rock mechanical analyses was that the deposition tunnels had to be orientated in parallel to the mean value of the direction of the highest principal stress. Deformation zones and associated respect distances had a great influence on the layout. When developing the layout shown in Figure 2-3 only fracture zones with high or medium confidence were taken into account and the total portion of abandoned deposition holes was assumed to be 10%. Later analyses based available flow and rock structural models taking into account water inflow criteria and distance to local minor fracture zones for deposition holes indicated much higher rates of abandoned holes than what was assumed when developing the layout but these figures have not been used.

Preliminary assessment of rock support and grouting does not differ significantly from earlier generic assumptions.

A number of conclusions for the future can be drawn from the preliminary analyses made:

- Rock mechanical analyses showed that rock stresses had a great impact on both the orientation of tunnels and the number of depositions holes that had to be abandoned because of rock burst. The criterion for determining the risk for rock burst is very important.
- The strike and dip of fracture zones and the respect distance to them had a great influence on the layout.
- It is very important that DFN models are reliable as a number of analyses are based on these models.

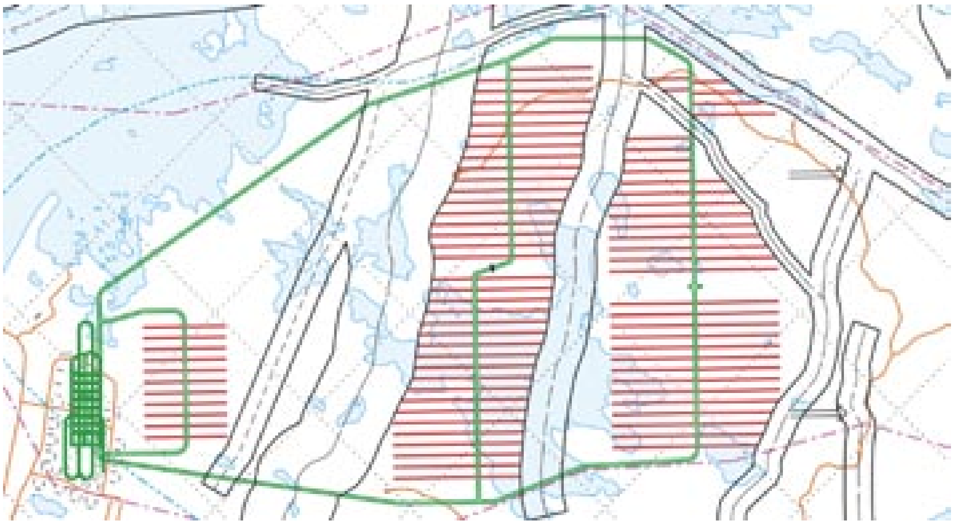

Figure 2-3. *Repository layout at 400 m level in Forsmark.*

- The operational area on ground should be located in the centre of the repository deposition areas both to avoid the costs for excavating long access and transport tunnels at repository level and create an efficient facility. The location of the central service area however determines the location of the operational area at ground level due to the connections with a number of shafts in the reference design.

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 fule are to be deposited in the repository. For the option with 40 years of reactor operation the quantity of BWR fuel is estimated at 7200 tonnes and the quantity of PWR fuel at 2300 tonnes /SKB, 2003/. In addition 23 tonnes of MOX fuel and 20 tonnes of fuel from the reactor in Ågesta will be deposited. The fuel burn-up may vary from 15 MWd/kgU up to 60 MWd/kg /SKB, 2001/.

Cast iron insert and copper canister

SKB's reference canister is 4.8 m long and has a diameter of 1.05 cm. It consists of an inner container of cast iron and a shell of copper. The cast iron insert provides mechanical stability and the copper shell protects against corrosion. 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. Canister BWR and PWR assemblies weigh 25 and 27 tonnes, respectively.

Buffer

In the deposition holes, the canister will be surrounded by a buffer of bentonite. The buffer is supposed to protect the canister. SKB has not made a final choice of buffer material and two different bentonites 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).

Bottom plate in the deposition holes

The bottom of the deposition hole will be levelled off with a grouted concrete plate. The bottom plate forms a stable foundation for the bentonite blocks and rings in the deposition hole. The thickness of the plate is > 5 cm.

Deposition tunnel

The deposition holes are drilled in the floor of the deposition tunnels. The cross section of the deposition tunnels mainly depending of size of the deposition machine. Further the shape of the tunnel will be depending on the excavation technique and rock stresses. SKB has not made a final choice of excavation technique yet and two techniques are analysed in SR-Can. The deposition tunnels are either excavated by careful drill and blast or by mechanical excavation by a tunnel boring machine (TBM). With the present design of the deposition machine the cross-section of the TBM bored tunnel is circular and has a diameter of 6–6.65 m whereas the cross-section of a drilled and blasted tunnel is 5.5 × 5.5 m 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 will be analysed in SR-Can. One concept is to backfill the entire tunnel section with a mixture of 70% crushed rock and 30% bentonite of the same type as the buffer. The material is compacted in situ. The other concept is to place prefabricated blocks of 100% natural Friedland clay in the tunnel.

Other repository cavities

Repository cavities other than deposition tunnels will be backfilled at the closure of the repository. Theses cavities, access ramp, shafts, central area and 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. The analyses in SR-Can are based on the assumption that the other cavities are backfilled with the same materials as the deposition tunnels.

Repository plugs

Three types of plugs may be used in the repository, operating plugs, plugs with a permanent function and plugs for preventing human intrusion after final sealing and closure of the repository. The operating 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. These plugs 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 investigations.

Investigation boreholes

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. Sealing with bentonite plugs will be analysed in SR-Can.

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. At the beginning of 2003 approximately 5700 tonnes of spent fuel have been generated /SKB, 2003/. With an operating time of 40 years for all reactors, except for Barsebäck 1 which was taken out of operation during 1999, the total quantity of spent fuel can be estimated at 9500 tonnes /SKB, 2003/.

Fuel types

Several types of fuel will be emplaced in the repository. For the alternative with 40 years of reactor operation, the fuel quantity from boiling water reactors, BWR fuel, is estimated at 7200 tonnes, while the quantity from pressurized water reactors, PWR fuel, is estimated at about 2300 tonnes /SKB, 2003/. In addition, 23 tonnes of mixed-oxide fuel (MOX) fuel with German origin from BWR and PWR reactors and 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.

The fuel burn-up are expected to vary from about 15 MWd/kgU up to 60 MWd/kg /SKB, 2001/. The burn-up distribution in CLAB in April 2003 is given in Figure 3-1.

Table 3-1. Amount of spent fuel and number of fuel elements /SKB, 2003/.

Fuel type	Amount spent fuel (tonnes of U)	Number of fuel elements/units
BWR	7203	39,730
PWR	2268	4900
MOX, Ågesta, Studsvik	23+20+2.4	640

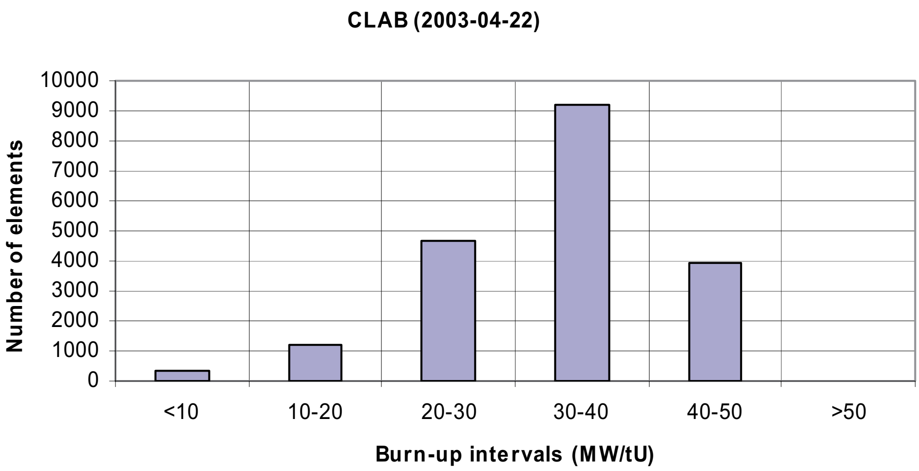

Figure 3-1. *Burn-up distribution in CLAB (April 2003).*

The MOX fuel has a higher decay heat than uranium fuel, which means that less fuel (tonnes) can be emplaced in each canister.

Differences between different fuel types are however important for criticality assessments.

Structure of the fuel assemblies

Nuclear fuel, here exemplified by BWR fuel (Svea 96), consists of cylindrical pellets of uranium dioxide. The pellets are 11 mm high and have a diameter of 8 mm. 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. Each assembly contains 96 cladding tubes. The fuel assembly also contains components 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.

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

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 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.

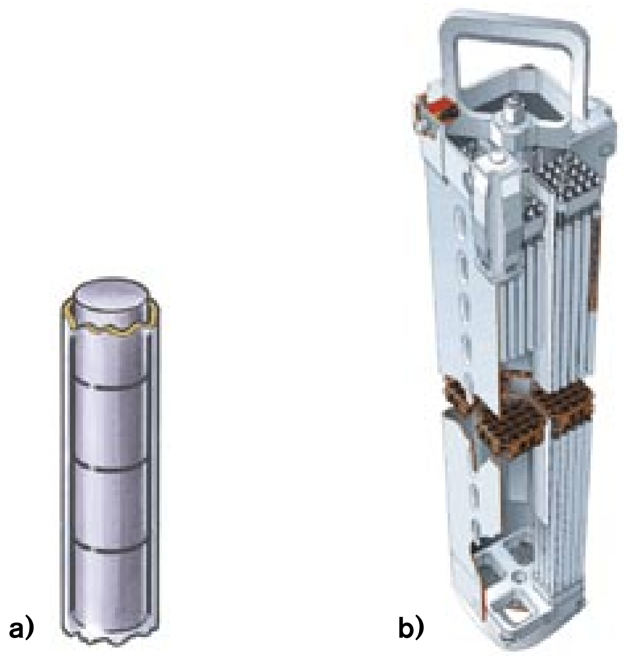

Figure 3-2. *a. Cylindrical fuel pellets in cladding tubes of Zircaloy. The pellets have a diameter of approximately one centimetre. b. Fuel assembly of type Svea 96. The assembly consists of 96 fuel tubes and has a height of approximately 4 metres.*

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.

BWR fuel and PWR fuel differs marginally regarding radionuclide content.

Cavity in canister

This repository sub-system comprise the spent fuel but also the cavity in the canister. The atmosphere in the cavity is air and water vapour. The water originates from defect fuel rods.

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.

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.

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 and flows)	Flows 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 initial state, i.e. the initial values of these variables including the tolerances, is described below. Variability in spent fuel characteristics between canisters (geometry, inventory, material composition, radiation intensity) is not discussed in this interim version of the report but is necessary to include in the final version of the report.

3.2.2 Geometry

Initial value

Detailed dimensions for the BWR and PWR reference fuels are found in data sheets 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 0.05% of the rods in the interim storage was reported to be defective in 1995 (500 defective rods of a total of one million in interim storage in CLAB) /SKB, 1995/. No additional defective fuel has arrived to CLAB after that (May 2004).

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 the fuel geometry will not change in a decisive manner.

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 in /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 percent. 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 is dependent on the radioactivity, i.e. the radionuclide inventory, and the fuel's geometry. Both of these variables are 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 difficult to estimate before all steps in the handling sequence have been established. It is estimated that the temperature will be somewhere between 200 and 400ºC /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 (pressure and flows)

Initial value

The hydrovariables, i.e. water pressures, water flows and gas flows are not relevant to describe initially. The gas pressure is discussed in Section 3.2.10.

Uncertainties

Not applicable.

3.2.6 Mechanical stresses

Initial value and uncertainties

The fuel pellets have inherent stresses caused by grain growth etc as a consequence of nuclear fissions and irradiation. The internal structure of the 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.

This affects the surface of the fuel pellets, which is of importance for the rate at which radionuclides can be released if the fuel comes into contact with water. Data for the safety assessment are based on surface determinations of spent fuel that has been affected by the above-mentioned processes and conditions.

3.2.7 Radionuclide inventory

Initial value

The inventory of radionuclides in the fuel can be calculated and the activity per tonne of fuel in the assemblies is given for the different types of fuel. An example of radionuclide inventories in BWR and PWR fuel at two different burn-ups (38 and 35 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/.

The radionuclide inventory for PWR and BWR fuel will be updated and complemented with the radionuclide inventory of MOX-fuel in the final reporting of SR-Can.

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. /Johnson and Tait, 1997/ have estimated the size of this fraction. These fractions and how large a portion of the inventory of the inventory is present in the structural parts of the fuel was reported in SR 97 /SKB, 1999/ and will be up-dated in the final version of the SR-Can reporting. 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 relatively small.

The surface fraction estimate used in SR 97 was based on experimental data from Canadian CANDU fuel in particular.

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 interim reporting but will be handled in the final reporting of SR-Can.

3.2.8 Material composition

Initial value

The composition of the fuel assemblies is given in detail in Appendix 1. The radionuclide inventory in the structural parts before and after operation can be found in the SR 97 reports /SKB, 1999; Håkansson, 1999/, see the section above.

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.

Uncertainties

Not applicable.

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 (dry air or noble gas), which means that the pressure in the canister cavity may be a couple of atmospheres if the initial temperature is as high as 400ºC. Water vapour: The maximum permissible quantity of water in a canister is now set to 600 grams. This value is equivalent to the void in one fuel rod and thus presumes that one Zircaloy cladding tube is defective during operation or interim storage.

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 600 grams. The consequences of an additional amount of water have to be evaluated and a possibility 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 inner container, the insert, of cast iron and an outer shell of copper, Figure 4-1. The cast iron insert provides mechanical stability and the copper shell protects against corrosion in the repository environment. The copper shell is 5 cm thick and the cylindrical canister has a length of approximately 4.8 metres and a diameter of 1.05 metres. 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.

A canister holds about two tonnes of spent fuel. Canister with BWR and PWR assemblies weigh 25 and 27 tonnes, respectively. A total of about 4500 canisters will be produced according to current estimates.

Fabrication of canister and encapsulation

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 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. The reference canister is foreseen to be fabricated with a seamless tube.

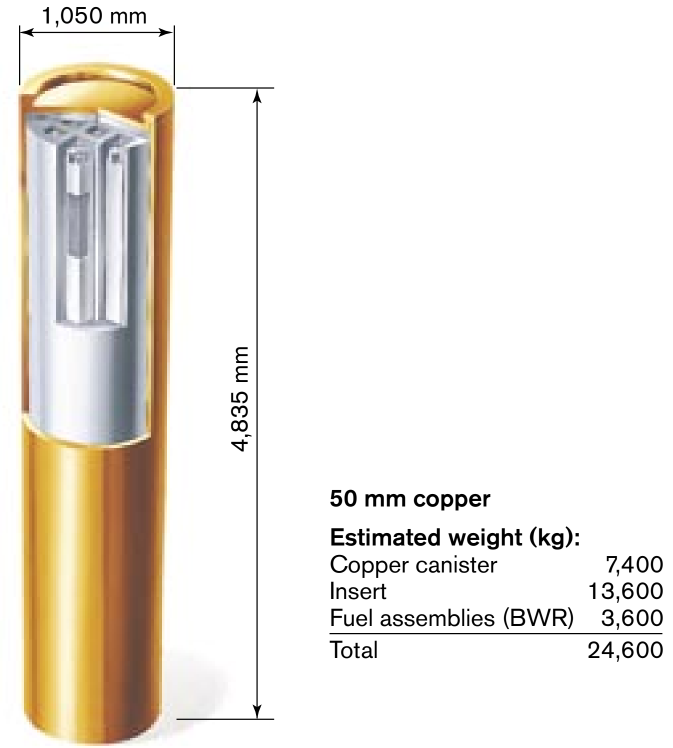

Figure 4-1. *Copper canister with cast iron insert.*

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, 2002/. 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 been 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 difference between the methods in the quality of the cast inserts has been observed thus 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 and ultrasonic testing are done before the insert is ready to be lowered into a copper tube with welded-on bottom. SKB has developed a technical specification for the fabrication of the insert, KTS 011 /Andersson, 2002/. The canister parts are shown in Figure 4-2.

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 set requirements.

Figure 4-2. *Canisters parts, cast iron insert, copper tube and lid.*

Welding of the lids and bottoms of the copper canister can be done either by friction stir welding (FSW) or by electron beam welding (EBW). Both methods have been demonstrated for welding of the canister bottom and FSW has been demonstrated also for the lid. The demonstrations have showed that both methods are promising and they are now being developed in parallel. The aim is to select welding method during 2005.

Methods for non destructive testing (NDT) of the canisters and welds are being developed. Examples of applied methods for this are radiographic and ultrasonic testing. After approved inspection the canister parts (copper canister with welded on bottom and insert, insert lid, and copper lid) will be delivered to the encapsulation plant.

The fuel will be placed in the canister in the encapsulation plant. The insert will be closed with an O-ring-sealed lid which will be fastened with a bolt. The copper shell's lid is then attached by welding, and the integrity of the weld is verified by ultrasonic and radiographic inspection.

Quality system

The quality system for canister fabrication and encapsulation is intended to cover the entire chain from material suppliers to delivery of finished canisters. 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. Methods for quality control are developed both for applied standard methods for non-destructive testing methods.

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 subsystem mechanically and material compositions for insert and canister characterise it chemically. The variables are defined in Table 4-1.

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.

4.2.2 Canister geometry

Initial value

A summary of geometry for both the BWR and PWR versions of the canister are given in Table 4-2 /Andersson, 2002/. The geometry of the BWR version is shown in Figure 4-1.

This variable also includes the geometries of potential initial defects e.g. in the welds. An evaluation of test welds performed at the canister laboratory in Oskarshamn with both friction stir welding and electron beam welding is in progress. Information is collected on types of failures and frequencies. This information will be added in the final version of this report.

Uncertainties

Uncertainties in the initial geometry of the canister primarily concern canister integrity. The canisters are fabricated, sealed and inspected with methods that guarantee that no more than 0.1 percent of the finished canisters contain discontinuities that are greater than what is permitted by the acceptance criteria for non-destructive testing /Werme, 1998/. The safety assessment therefore assumes that no more than one canister in a thousand has a defect of that kind, for example a non-penetrating cavity in the lid welds.

The probability of a defect is greatest in the lid weld, since the possibilities of inspection and testing are better for the bottom weld.

Table 4-2. Geometry of the assembled canister.

Canister	
Length:	4835 mm
Diameter:	1050 mm
Total weight (including fuel):	24,600 kg (BWR) 27,000 kg (PWR)
Copper tube	
Wall thickness:	50 mm
Inner length:	4575 mm
Inner diameter:	953 mm
Lid thickness:	50 mm
Bottom thickness:	50 mm
Cast iron insert	
Length:	4573 mm
Diameter:	949 mm
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)

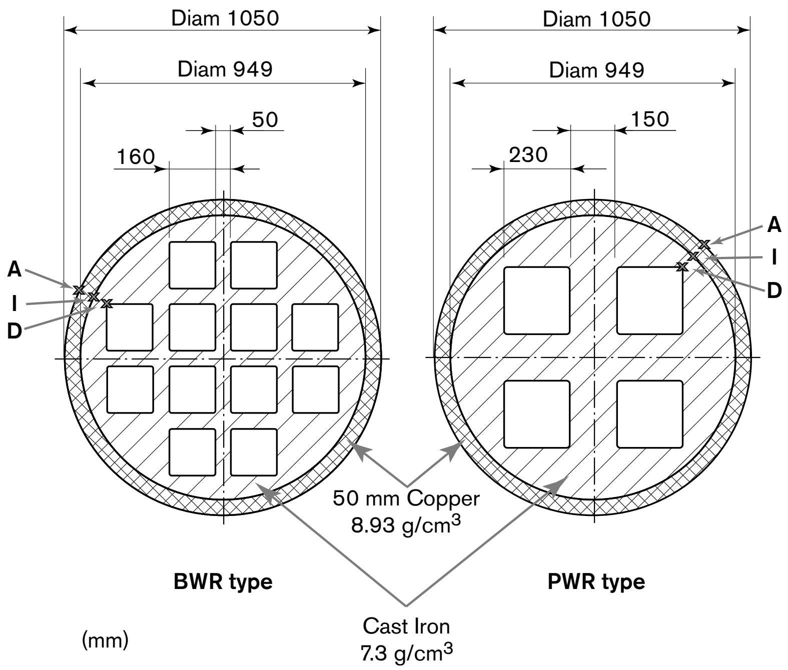

Figure 4-3. *Schematic design of insert for 12 BWR or 4 PWR assemblies for a 50 mm thick copper shell.*

4.2.3 Radiation intensity

Initial value

The dose rate caused by γ and neutron radiation outside the canister has been calculated by /Håkansson, 1996/. A canister with 40-year-old fuel emits γ and neutron dose rates of 350 and 20–40 mGy/h, respectively.

Uncertainties

/Lundgren, 1997/ compares different calculations of radiation doses around the canister. The values vary between 100 and 500 mGy/h for γ radiation at different positions on the canister surface, due among other things to the fact that the insert is not cylindrically symmetrical.

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.

4.2.4 Temperature

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 1700 W, to fulfil set temperature requirements at the canister surface in the deposition hole.

Uncertainties

The main uncertainties come from relatively large uncertainties concerning the heat transfer from the canister surface to the surrounding bentonite. Once the bentonite in the deposition hole has been fully saturated, the uncertainties are considerably reduced.

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.

4.2.6 Material composition

Copper shell

SKB has compiled technical specifications with requirements on the copper material, KTS 001 /Andersson, 2002/ for ingots and billets and KTS 002 /Andersson, 2002/ for manufactured copper components. 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 4-3) or Cu-OF1 (Table 4-4) with the following additional requirements: O < 5 ppm, P = 30–70 ppm, H < 0.6 ppm, S < 8 ppm and that the grain size shall be ≤ 360 μm in forgings for lids and bottoms as well as in the tubes.

Table 4-3. 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 4-4. 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 percent 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-400-14U. The steel lids are produced from steel plates and the plate shall be according to EN 10025 S355J2G3 or similar grade. The chemical composition (see Table 4-5) 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.

The material specifications for profiles forming the steel section cassette (channels for fuel assemblies) coincides with the requirements in EN 10015 S355J2H or SS 14 21 34-03 or SS 14 21 34-04. 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, 45 MPa with sufficient safety margins. Incorrect graphite structure will have a stronger impact on the mechanical strength of the insert.

Table 4-5. 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

In the deposition holes drilled in the bottom of the deposition tunnel the copper canister will be surrounded by a buffer of clay. 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 deposition, gaps 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 in 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.

Drilling of deposition holes

The drilling of the deposition holes can start when the deposition tunnel is excavated to its full length. The deposition hole excavation work begins with core drilling of a pilot hole in the intended centre positions for the deposition holes, in order to check that the rock is suitable. The position of the deposition hole is then marked in the roof of the tunnel. A levelling concrete slab, approximately 2.5 × 2.5 metres, 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 entering the deposition hole later. While this work is being done, the floor of the tunnel is levelled with macadam in preparation for heavy loads. After approval of the drilled rock core sample the deposition holes are drilled, using a TBM machine or similar equipment. The drilling machine is centred over 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. All holes in the deposition tunnel will be drilled before deposition of buffer and canisters can start. The deposition hole has a diameter of 1.75 m and a depth of about 8 m.

After completion of the drilling 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 will be required later for determine the final density of the buffer after saturation.

Manufacturing of buffer

The important aspect in the manufacturing of bentonite blocks and rings and the deposition process is to get a final density in the water saturated buffer. The density required for the saturated buffer in SR-Can is 1950–2050 kg/m^3.

The bentonite will be bought in bulk form and transported by ship to a suitable harbour. The bentonite will be subject to quality control before loading in the ship and the material will be analysed and approved at reception.

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. Equipment to fabricate full size buffer components with isostatic pressing is not available in Sweden today.

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. 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 before the bentonite powder is filled into the bags for the isostatic press.

The bentonite blocks will be manufactured to a dry density that gives the correct final density 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 of material

It is important to select a supplier of bentonite that is able to deliver a material with an even quality and does 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 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 delivery of an 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 have 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.

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 top bentonite block 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 s 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 effect 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. The density of the buffer could be 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 method, which has been tested in the Prototype Repository in Äspö HRL, is a plastic bag inserted to surround and protect the whole buffer, see Figure 6-1. In addition, a small drain tube is inserted in the slot in the periphery of the concrete bottom plate (see Figure 6-1 in Chapter 6) at the bottom of the deposition hole.

The bag and drainage equipment 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 plastic bag will be kept sealed until the start of backfilling of the deposition tunnel. 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 backfill 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.

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 to 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 in 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 the 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 1000 kg/m^3 and density of clay solids (ρ_{cs}) is 2780 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 (pressure and flows)	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.

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 barrier thickness required to obtain the expected function. The dimensions of the canister is given, see 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 height of 50 cm, since higher blocks and rings cannot be produced today, see Figure 5-1. The bentonite units have a diameter of 1690 mm and the thickness of the rings is 315 m. One bentonite block is placed below the canister, nine rings surround it and four blocks are placed above the canister. The bottom and top of the canister are not even and the blocks placed below and above the canister must be processed to fit the canister geometry properly. The final buffer geometry after saturation is shown in Figure 5-2.

Slots

The slot between the canister tube and the buffer is 5 mm and the slot along the radial boundary between the buffer and the rock is 30 mm. The slots are left empty.

Figure 5-1. Control measurement of bentonite ring.

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

Bentonite blocks and rings	Number of blocks/rings	Diameter (outer), mm	Diameter (inner), mm	Height, mm
Below canister (block)	1	1690	-	500
Around canister (rings)	9	1690	1060	500
Above canister (blocks)	4	1690	-	500

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 5-2):

- Diameter: 1750 mm.
- Depth: ~8000 mm.
- Shape: ~0.00125 ($\Delta d/l$).
- Discrepancy in vertical line at the bottom of the hole: <16 mm.

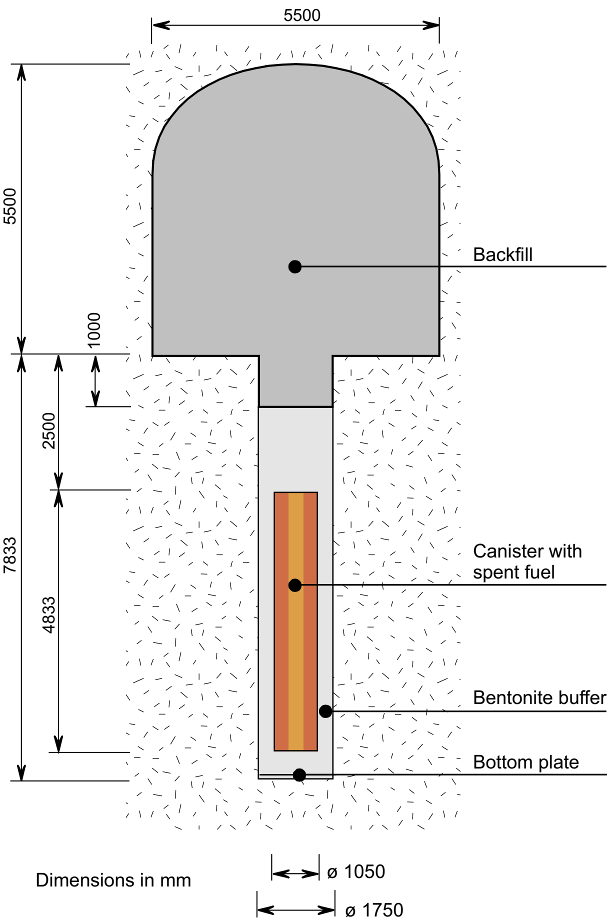

Figure 5-2. *Deposition hole with bentonite buffer and canister.*

Uncertainties

The dimensions (and densities) of the blocks are settled to yield a density after saturation and homogenisation of 1950–2050 kg/m^3. Pieces of rock that have fallen from the surface will increase the volume and decrease the final density. Small pieces may also have been lost from the blocks.

Further, if the deposition hole do 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 achive the required final density. It would also be possible to add granular bentonite in the gab between the rock surface and the pile of bentonite.

5.2.3 Pore geometry

Initial values

The void ratio (e) is given by the dry density and the density of the different phases.

Blocks: e = 0.680

Rings: e = 0.585

Uncertainties

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

Blocks: Δe = ± 0.015

Rings: Δe = ± 0.015

There is also an internal variation in the blocks mainly due to variation in water ratio and due to friction against the walls of the mould during compaction. This variation is also estimated to be about Δe = ± 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 (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 200 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 undisturbed 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 bentonite blocks and rings have an initial value of water content (w), weight of water divided to the weight of dry mass of 17%. Since the initial dry density (ρ_d) is different for the rings and the blocks the degree of water saturation (S_r) will be different.

Blocks: ρ_d = 1655 kg/m^3, S_r = 70%

Rings: ρ_d = 1754 kg/m^3, S_r = 81%

Slots: All slots are empty from start (no artificial water filling).

Uncertainties

The water content in the blocks and rings may vary ± 0.5%.

5.2.7 Gas content

Initial values

The unfilled 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

Same as for the water content but reverse, which means a variation in gas content of ±0.8%.

5.2.8 Hydrovariables (flows and pressure)

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

Initial values

The initial water pressure in the bentonite block and rings is 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 in the air in the slots are assumed to be the same as in the buffer that is a relative humidity (RH)~75%, which 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 ratio (Δw) ± 0.5% yields a variation in relative humidity (RH) of about ± 1%, which yields a variation in water pressure (Δu) of about ±1800 kPa.

The air in the tunnel may be wetter or dryer than 75% relative humidity (RH), which may cause a different initial relative humidity in the air in the slots. The influence of such deviation on the behaviour after deposition is though insignificant. It is however very important that the blocks are not exposed to a different relative humidity for 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: σ' = 28 MPa

Rings: σ' = 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

MX-80 bentonite

The mean composition of the examined MX-80 bentonite brand is given in Table 5-3. In addition, grains of pyrite (FeS2), calcite (CaCO3), siderite (FeCO3), barite (BaSO4) and iron hydroxides in mean quantities less than 1%, respectively.

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

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 above values.

Table 5-3. Bentonite composition of MX-80 and Deponit CA-N.

Component	MX-80 (wt-%)	Deponit CA-N (wt-%)	Uncertainty (± wt-%)
Calcite + Siderite	0	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
CEC (meq/100g)	75	70	2
Organic carbon	0.2	0.2	–

5.2.11 Montmorillonite composition

Initial values

MX-80 bentonite

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 mole-weight of the montmorillonite based on an $O_{20}(OH)_4$ cell is 750 g and the layer charge –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

The CEC is 0.70 eq/kg for the total Deponit CA-N material, and 0.85 eq/kg for the clay fraction. The mole-weight based on an $O_{20}(OH)_4$ cell of the montmorillonite is 751 g and the layer charge –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 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.
- 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 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 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 structural materials will be left in the deposition hole since the concrete bottom plate is a sub-system of its own, see Chapter 6.

Potential stray materials in the deposition holes are oil spillage (hydrocarbons) from the excavation of the deposition holes and human waste e.g. urine (carbonhydrate). 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 left oil 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 better estimates of the amounts are planned for the purpose of the final version of this report.

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 uncertain, how this amount is distributed between the rock walls, cuttings, and cleaning water.

The amount of oil spillage on the bentonite blocks from the fabrication is expected to be very small.

6 Bottom plate in deposition holes

6.1 General

The bottom of the deposition hole will be levelled off with a cast concrete 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 bottom plate will be cast of concrete containing low pH cement. The development of suitable cement is in progress but a final recipe is presently not available. 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.

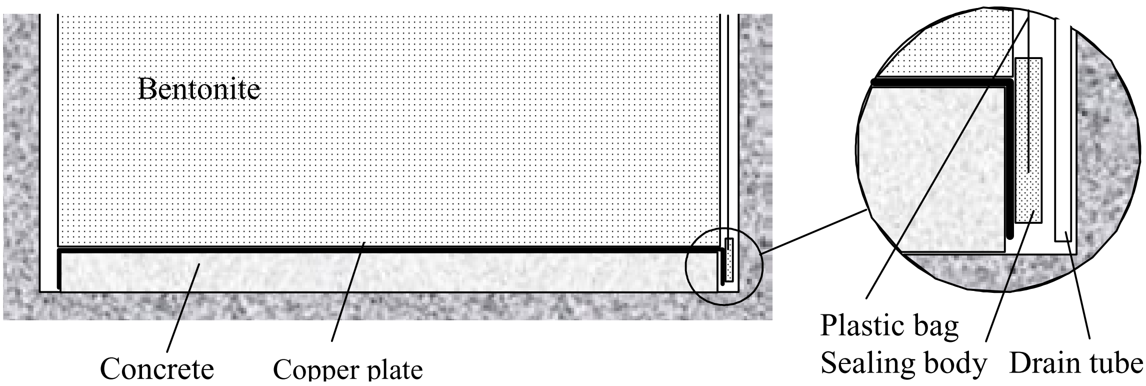

Figure 6-1. *Bottom plate in deposition hole.*

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. The thickness of the cast 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 is left between the concrete bottom plate and the rock wall. The copper plate on top is a few millimetres thick.

The void ratio (e) in the concrete bottom plate is estimated to be e ~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 hole.
Hydrovariables (pressure and flows)	Flows and pressures of water and gas as a function of time and space in concrete bottom plate in deposition hole.
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 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 % of water content. The water pressure in the bottom plat will be 0 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. However, the plate will be drained in order to avoid such a scenario.

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-pH concrete. The development of a recipe for the low pH cement is in progress but is presently not available. The concrete in the surface layer of the bottom plate must flatter out to be horizontal.

The copper plate is made of similar material as the canister, see Section 4.2.6.

6.2.7 Pore water composition and content

Initial value

The pore water composition and content can presently not be specified.

7 Backfill of deposition tunnel

7.1 General

When all holes in a deposition tunnel have been filled with canisters 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.

Excavation of the deposition tunnel

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 analysed in SR-Can. If drill and blast technique is selected, this will be done carefully in order to minimize the damage of the rock at the runnel 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 could be 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 could need excavation in two steps, first a gallery and then a bench. The methods for excavation and verification of the excavated disturbed zone (EDZ) need to be studied more in detail in the future.

The excavation technique will have implications on the dimensions and shape of the deposition tunnel (see Section 7.2.2). The excavated tunnel will be controlled by laser scanning (digital measurement) for characterization of the deposition tunnel and to determine the fracture systems. This will also give the actual dimensions of the tunnel and the deviation from the theoretical values. This information would later on be used for determine the amount of backfill material that has to be used during backfilling of the tunnel.

Backfill concepts

Two different backfill concepts will be analysed in SR-Can:

- Mixture of crushed rock and bentonite. The entire tunnel section is backfilled with a mixture of 70% crushed rock and 30% bentonite of the same type as the buffer, see Figure 7-1. The material will be compacted in situ. The concept will have a final clay fraction density of around 1600 kg/m^3 when water saturated. The upper metre of the deposition holes is backfilled with the same material as the tunnel.
- Blocks of Friedland clay. The entire tunnel section is backfilled with pre-compacted blocks made of 100% Friedland clay. The upper metre of the deposition holes will be filled with bentonite blocks made of the same material and with the same dimensions as the buffer bentonite block emplaced above the canister.

Rejected deposition holes are backfilled in the same manner as the upper metre of the used deposition holes.

Manufacturing and control procedures

Manufacturing and control procedures are here exemplified in a description valid for a backfill mixture of crushed rock and bentonite. The bentonite in bulk is transported from the harbour to an indoor storage (dry and temperature kept above 15°C) where the material is moved from the container to pockets that convey the material on to the production facility with a bentonite mill. After milling and sieving the bentonite is blown to silos. The silo will be equipped with a fluidisation devise that facilitates the discharging from the silo.

The frost free rock storage facility would be placed in parallel to the production facility. The material is transported with front end loader to the charger for a crushing equipment. After crushing and sieving in several steps the material is transported to silos.

Mixing of crushed rock and bentonite is made batch wise in a mixing equipment and the mixed material is transported to the repository level with trucks, possibly in containers. Moister measurement of the bentonite will be made. The control system estimates the necessary amount of water from the actual water ratio in the mixture and the desired water ratio. The dosing and weighing of bentonite is 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 of the composition of the material can be made in three stages:

- 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 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 the recipe that are delivered from the mixing plant. When 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.
- Samples are also taken after the emplacement in the tunnel to ensure that the homogeneity of the mixture is still good.

Figure 7-1. *Backfill of crushed rock and bentonite. Left photograph shows Backfill and Plug test in Äspö Hard Rock Laboratory. Right photograph shows in situ compaction in Prototype repository in Äspö HRL.*

A description of the manufacturing and control of backfill material in the other concept will be added in a next version of this report.

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 subsystem is constrained also by the rock around rejected deposition holes.

The backfill in the deposition tunnel as it is delimited by the variable backfill geometry is characterised thermally 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. The following values have been used: density of water (ρ_w) is 1000 kg/m^3, density of clay solids (ρ_{cs}) is 2780 kg/m^3, and density of crushed rock solids (ρ_{rs}) is 2700 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. The final decision about which excavation technique to use has not yet been taken and two possible techniques, drill and blast or mechanical excavation (TBM), are analysed in SR-Can. The cross section in a drill and blast deposition tunnel is a square with an arched roof, whereas the cross section in a mechanically excavated tunnel is circular. The dimensions of the deposition tunnel and the upper one metre of the deposition holes and rejected deposition holes are given in the Table 7-2. Three deposition hole positions in each tunnel are assumed to be rejected. Normally these positions are rejected based on core drilling, and the deposition holes are not drilled.

Mixture of crushed rock and bentonite

The backfill fills the entire tunnel and the upper metre of the deposition holes. The limits are thus the rock and the top surface of the upper bentonite block.

Pre-compacted blocks of Friedland clay

This concept consists of blocks and slots between the blocks and at the rock surface. The deposition tunnel is filled with blocks (density ρ_d = 2100 kg/m^3, water ratio w=3%) and with an average "degree of filling" of 80% in order to yield the final density. If the blocks can be placed directly on the floor and the internal slots between the blocks are assumed to be only a few per cent, the average slot between the roof and the walls will be 15–20 cm.

The upper metre of the deposition holes will be filled with two blocks identical to the blocks in the buffer (see chapter 5.2.2).

The size and shape of the blocks for placement in the tunnel has not been determined yet, but in the ongoing investigations square blocks with an approximate volume of 0.25 m^3 has been considered.

Table 7-2. Dimensions of deposition tunnels /SKB, 2002/.

	Height and width or diameter (m)	Cross section (m^2)	Length per deposition tunnel (m)	Total volume (m^3)1)
Deposition tunnel			265 (+50/–100)	
Drill and blast	5.5 x 5.5	25		920,000
Mechanical excavation	Ø 6–6.5	28–33		945,000–1,100,000
Deposition hole, upper 1 metre (37 holes per tunnel)	Ø 1.75	2.4 [2)]	37×1=37 [2)]	10,900 [3)]
Rejected deposition holes (3 holes per tunnel)	Ø 1.75	2.4 [2)]	3×8=24 [2)]	7000 [4)]

[1)] 22×145+114×265=33400 m deposition tunnels
[2)] calculated value
[3)] calculated value (=94,000×37/40/8)
[4)] calculated value (=94,000×3/40), normally these positions will be rejected based on core drilling

Uncertainties

It has to be determined if the density is high enough to fulfil the requirements if 20% of the tunnel volume is void.

7.2.3 Backfill pore geometry

Initial values

Mixture 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.

$e = 0.59$

$S_r = 54\%$

Pre-compacted blocks of Friedland clay

The void ratio (e) and degree of water saturation (S_r) in the blocks are

$e = 0.33$

$S_r = 27\%$

In addition 20% of the total volume consists of unfilled voids, of which a few are voids between the blocks.

Uncertainties

Mixture of crushed rock and bentonite

The variation of the void ratio in a vertical section of the tunnel is rather high with the lowest void ratio in the centre and the highest at the roof. The present estimation is that the void ratio may vary between 0.7 and 0.5.

Pre-compacted blocks of Friedland clay

The variation in void ratio (Δe) is +/– 0.017% in the pre-compacted blocks. The void ratio in the total tunnel cross section will be much higher due to the 20% of the volume that is filled with voids.

7.2.4 Temperature

Initial values

The tunnel backfill 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 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°. This is of no importance to the thermal evolution in the repository.

7.2.5 Water content

Initial values

Mixture of crushed rock and bentonite

The water ratio (w) 12% will be used for having the best compaction properties. With the average dry density (ρ_d) of 1700 kg/m^3 the average degree of water saturation (S_r) will be 54%.

Pre-compacted blocks of Friedland clay

This concept consists of blocks and slots between the blocks and at the rock surface. The deposition tunnel is filled with blocks (density ρ_d = 2100 kg/m^3, water ratio w=3%) and with an average "degree of filling" of 80% in order to yield the final density. If the blocks can be placed directly on the floor and the internal slots between the blocks are assumed to be only a few per cent, the average slot between the roof and the walls will be 15–20 cm.

Uncertainties

Mixture of crushed rock and bentonite

The variation in water ratio (Δw) is ± 1%.

Since the density will vary in a section with the highest density in the centre and the lowest at the roof the degree of saturation will vary accordingly.

Pre-compacted blocks of Friedland clay

The variation in water ratio (Δw) is ± 0.5%.

7.2.6 Gas content

The unfilled pores will be filled with air and the gas content is calculated as the volume gas divided to the total volume.

Initial values

Mixture of crushed rock and bentonite

46% of the pores are air-filled, which for the actual dry density yields a gas content of 17%. No slots at the rock surface.

Pre-compacted blocks of Friedland clay

73% of the pores in the blocks are air-filled which yields a gas content of 24%. In addition 20% of the total volume consists of air-filled slots between the blocks and at the rock surface.

Uncertainties

Mixture of crushed rock and bentonite

Since the density will vary in a section with the highest density in the centre and the lowest at the roof the gas content will vary accordingly.

Pre-compacted blocks of Friedland clay

The variation in water ratio (Δw) is ± 0.5% in the blocks, which yields a variation of ± 0.06% of the gas content in the blocks. The variation of total volume of the unfilled slots in a vertical section of the tunnel depends mostly on the variation in sectional tunnel area caused by the blasting irregularities. This variation is not clear today, but depends largely on the blasting technique and the rock properties.

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

Mixture of crushed rock and bentonite

The water ratio (w) 12% of the backfill yields a negative water pressure (u) of -3000 kPa.

Pre-compacted blocks of Friedland clay

The water ratio (w) of the blocks 3% 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

Mixture of crushed rock and bentonite

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

Pre-compacted 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 ± 1800 kPa.

7.2.8 Stress state

Initial values

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.

Internal stress in the Friedland clay blocks: 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 in situ compacted backfill cannot be treated in the same way since the bentonite phase has a too low density. The initial stresses in this concept are probably best described as the total stress originating from the weight of the overlying material.

Vertical total stress: $\sigma_v = z \cdot g \cdot \rho$, where z = distance to the roof and ρ = bulk density.

Uncertainties

The in situ compacted parts have stresses built into the material by the compaction energy. However, these stresses are difficult to take into account and can probably be ignored.

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 of analysed natural Friedland clay is mixed layer minerals 45%, quartz 24% mica 13%, feldspar 5%, cabonates 2%, pyrite 1–4%, 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 relatively homogeneous and the content of favourable minerals can likely be kept constant. The complex mineralogy may possibly lead to varying contents of accessory minerals. 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 1.1 of the site descriptive models for Forsmark, Section 5.1 and 7.2 /SKB, 2004a/. 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 and a grain size distribution according to Figure 7-2.

The total content of backfill is determined by the excavated volumes (m^3), see Table 7-2 and estimates of left voids, see Section 7.2.2.

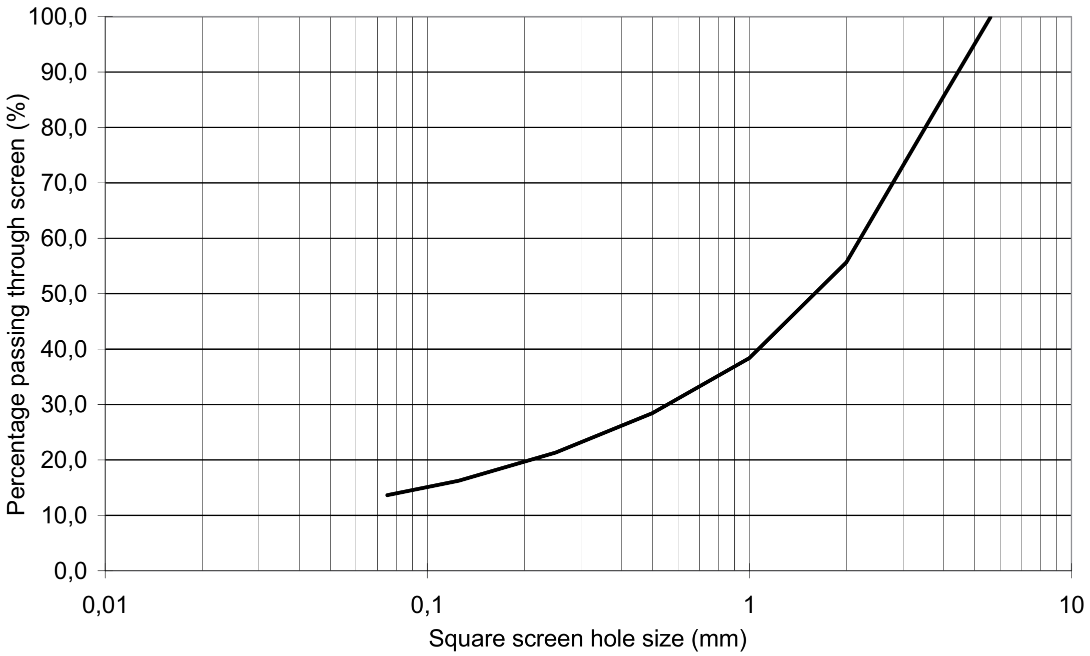

Figure 7-2. *Grain size distribution of crushed rock.*

Uncertainties

The composition of natural Friedland clay is relatively uncertain. See also Section 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 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 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 e.g. 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 bolts and reinforcement nets will be used as rock support. 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 are removed before closure of the deposition tunnel e.g. roadbeds. In addition, the tunnels are cleaned with highly pressurised water before the emplacement of the backfill starts. Concrete in the grout holes are left as part of the sub-system.

The estimations of the amounts of structural material are based on the same prerequisites as the economic calculations in Plan 2003 and the designed service life time of the deposition tunnels i.e. five years. Further the estimations of the rock reinforcements are based on the assumption that the tunnels are excavated by drill and blast. The need of reinforcements around a TBM tunnel is in general less, but the deposition tunnels are build in good rock and the aim is to minimize the amounts, therefore the differences are assumed to be marginal.

Initial values and uncertainties

Rock bolts

Rock bolts are used to tie unstable or potentially unstable rock structures in the tunnels. The rock bolts in the deposition tunnel may be of the Swellex type which are anchored without grout. The diameter of the boreholes is normally 48 mm.

The amount of rock bolts needed vary with the quality of the rock and rock stresses. The following intervals give an indication of how much rock bolts may be needed in a deposition tunnel:

- Number of bolts per 100 metre tunnel: 0–200 (average 100).
- Length of bolts: 3 m.

The rock bolts are made of steel and an example showing a possible chemical composition is given in Table 7-3. One of the primary causes of rock bolt failure is corrosion of the bolts.

Table 7-3. Example of chemical composition of steel rock bolts (Swellex, EN 10025 S355JR).

(% wt max)	Fe	C	Si	Mn	P	S
EN 10025 S355JR	Remaining	0.24	0.55	1.06	0.045	0.045
		Cr	**Cu**	**Ti**	**V**	**N**
		-	-	-	-	-

Nets

Nets are made of steel (Ks 40 Steel) with an average thickness of 6–8 mm. No estimates of the potential amounts are presently available.

Grout holes

Sections of the rock around the deposition tunnel needs to be grouted, to decrease the water inflow to the tunnel. Small fractures (< 100 mym) in the deposition tunnel will be grouted with Silica Sol and larger fractures with cement based grout giving low pH leachates. 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 rock sections that need grouting are located by drilling of characterisation boreholes prior to the excavation of the tunnel. 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.

In average, the total amount of grout in each grout hole fan array is estimated at two tonnes, where of 50% is assumed to stay in the grout holes and 50% penetrate into the fractures in the geosphere. Each grout hole fan array consists of about 20 grout holes, 0.048 m in diameter and 15 m in length. The average amount of grout in grout holes in the deposition tunnel is 4 kg per metre. The uncertainties in this estimate are very large since the need of grout has a strong coupling to local site specific characteristics.

The recipe for the grout based on low pH cement is presently not available but a possible solution, which is being tested and evaluated by SKB and Posiva in co-operation is a mixture of the Ultrafin 16 (600 g), GroutAid (825 g), gypsum (24 g) and aluminium cement (45 g). This mixture does not contain organic additives. The compositions of the main grout products are given in Table 7-4.

Table 7-4. Examples of chemical composition of low pH grout materials.

Product name	Type	CaO wt%→	SiO_2	Al_2O_2	Fe_2O_3	SO_3	Na_2O	Others
Ultrafin 16	Sulfate resistant Portland cement	64.8	22.3	3.4	4.3	2.4	-	2.8
Silica Sol	Colloidal silica		~100					
Grout Aid	Silica slurry, aqueous solution	-	86	-	-	-	-	C ≤ 2.5

Stray materials

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. Drill and blast excavation would in addition to oil spillage also include spillage of explosives, detonators etc.

Spillage of oil is very much a matter of preventive maintenance, age of equipment, operator skill etc. Some information on typical spillage has been gained from drill and blast in mining and from construction project with TBM and a typical spillage would be around 0.01 l/m^3 of excavated rock i.e. around 10 m^3 of hydraulic oil for all deposition tunnels and less for lubrication grease.

To mitigate environmental impacts by spillage the following actions 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.

The use of degradable hydraulic oils and lubrication greases is an option. 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.

Excavation with drill and blast is associated with some spillage. Spillage from charging depends on how explosives are handled and on the type of explosive used. If emulsions and novel charging technology is used, spillage may be reduced to less than 1%. However not all explosives may detonate due to disturbances in the initiation of the holes, dead-pressing effects, breakage of neighbouring holes The total not detonated amount of explosives may be as high as 10–15% of the total charged weight i.e. around 200 tonnes of spillage of explosives for excavation of all deposition tunnels. The environmental concern is the emission of nitrogen, the main compound in explosives. The major bulk of the spillage will assemble in the tunnel floor muck, but around 1/3 may be released with the drainage water as the compound is soluble in water. In case the rock muck is used for backfill, these are easily 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 the 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 10% of the oil and explosive spillage is left in the deposition tunnel, i.e. around 1 m^3 of hydraulic oil for all deposition tunnels and less for lubrication grease, 20 tonnes of explosives.

Uncertainties

The information referred to is relatively uncertain and better estimates of the amounts are planned for the purpose of the final version of this report.

8 Backfill of other repository cavities

8.1 General

Other repository cavities, except deposition tunnels, e.g. access ramp and shafts, transport and main tunnels, ventilation shafts, and central areas (see Figure 8-1) which 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.

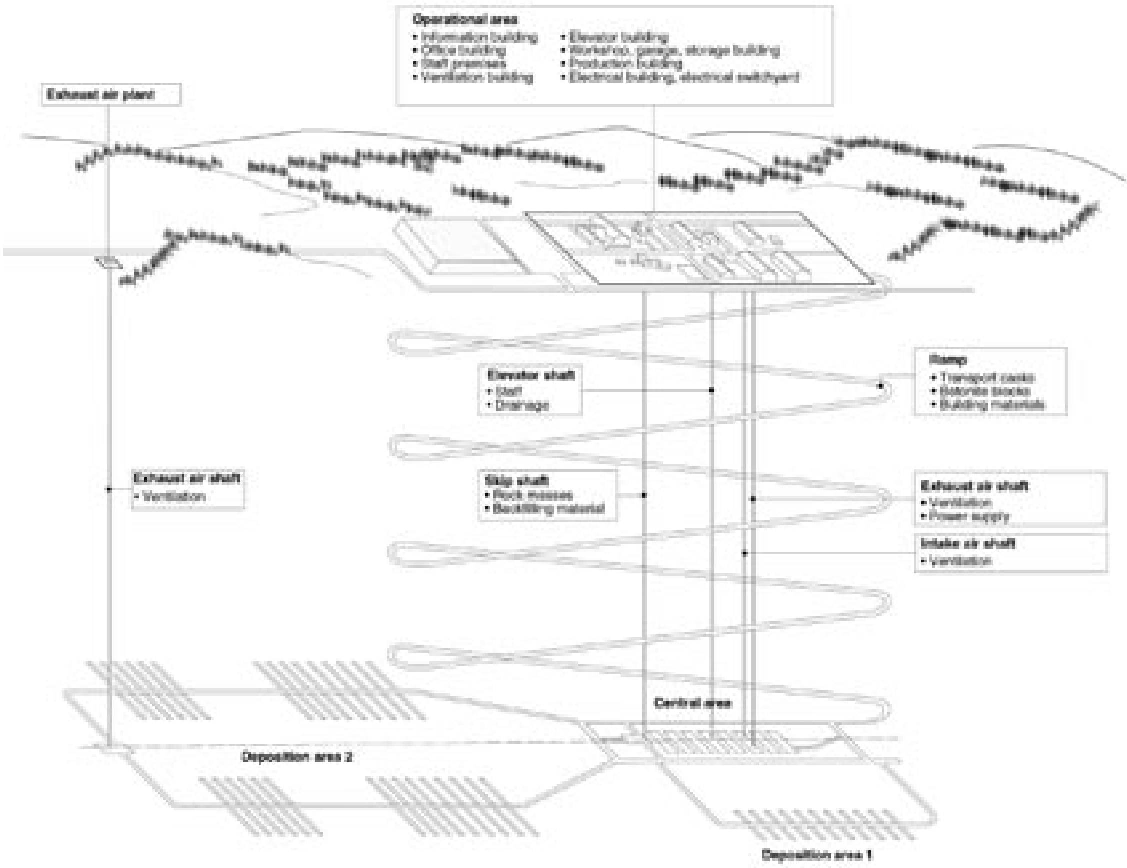

Figure 8-1. Layout of deep repository for spent nuclear fuel.

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 e.g. the main tunnels in the deposition area have interfaces to the plugs at the ends of the deposition tunnels.

The backfill in the cavities as it is delimited by the variable backfill geometry 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 1000 kg/m^3, density of clay solids (ρ_{cs}) is 2780 kg/m^3, and density of crushed rock solids (ρ_{rs}) is 2700 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/. 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 but has a number of passing places, 8 m high and 12 m wide, as well as other nisches. The total length of the ramp is 5000 m. Five shafts connect the repository and the surface, a skip shaft, three ventilation shafts and an elevator shaft. The shafts are all about 500 m deep 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 in diameter.

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

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. 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 (pressure 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) of the backfill in repository cavities (excluding deposition holes and deposition tunnels) 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 repository cavities.
Structural and stray materials	Chemical composition and quantity of structural (rock bolts, filling material in boreholes 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 cavities. Detailed dimensions are given in the facility description.

Repository cavity	Length (m^2)*)	Total length (m^2)	Width or diameter (m)	Height (m)	Area (m^2)	Volume (m^3)
Access ramp						290,000
Ramp,	5000	5000	7	7	46	230,000
passing places,	45	900	12	8	41	40,000
other niches, etc	4−5	170	3−6.5	3−4.4	9−20	20,000
Shafts						33,000
Elevator	-	-	Ø 5.5	560	24	12,000
Skip	-	-	Ø 5.5	510	24	13,000
Ventilation	-	-	Ø 3.5	500	10	5000
Ventilation	-	-	Ø 2.5	500	5	2000
Area for rock mass handling						8000
Silo						
Skip	-	-	Ø 7.7	19	47	700
Nisches, tunnel, etc	4.5	-	4.5	52	19	1000
	13−35	90	8−14	7−8	52−97	6000
Central area						130,000
Tunnels	110−295	1100	7−10	7	46−63	49,000
Passing places etc	8−32	170	8−12	7	11−16	2200
Vaults	8−208	560	3−14	3−16	8−218	80,000
Transport tunnels and ventilation shaft in deposition area						306,000
Transport tunnels	275−725	2100	7	7	46	76,000
Main tunnels	420−1120	2700	10	7	64	130,000
Others	8−2240		4−13	5−13	19−25	100,000
Ventilation shaft	-	-	Ø 3	500	32	700
Total						747,000

*) per unit/section

The central area is divided up into different vaults, each designed for its intended functions. The vaults are situated on transverse links between to parallel transport tunnels. The cross section of the vaults varies from 6 to 15 metres 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 – content and composition

For the purpose of SR-Can it is assumed that the backfill concept applied for the deposition tunnels are 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 (m^3), see Table 8-2 and the estimated voids in the applied backfill concept, see Section 7.2.3.

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 roadbeds will be removed but shotcrete, rock bolts, grout in grout holes will be left. The amount of rock reinforcements is determined by the excavation method, quality of the rock and the stress situation as well as the service-life time, which is 100 years for all cavities except deposition tunnels. The estimations of the rock reinforcements below are based on the assumption that the tunnels are excavated by drill and blast. The need of reinforcements around a TBM tunnel is in general less, but the differences are assumed to be marginal compared to other uncertainties.

Besides the construction materials, stray materials will be present in the deep repository in the form of spillage and waster products from machine use, contaminants from blasting, human refuse and materials introduced via the ventilation air etc.

Initial values

Rock bolts

Rock bolts are used to tie unstable or potentially unstable rock structures in the tunnels. The rock bolts anchored with grouting will be used.

The amounts of rock bolts as well as the amount of bolt anchoring grout/cement in the different cavities have been estimated, see Table 8-4. The rock bolts are made of steel and are 1.6–4.2 m long and 25 mm in diameter. The boreholes drilled in the rock walls are 48–51 mm in diameter. An example of the composition of a steel rock bolt is given in Table 7-3.

The anchoring grout is a low pH grout. Table 8-3 shows two examples of rock bolt grout recipes. The grouts have not been tested in laboratory or in situ and controls of e.g. creep have not yet been performed. Another concern is the lack of corrosion protection when using grout with low pH. The final composition of anchoring grout with low pH is not available but the development of it is part of SKB's research program and will therefore be specified in detail in the final version of this report.

Shotcrete

The roof and walls in the ramp, tunnels and other vaults are reinforced with shotcrete. The average thickness of the shotcrete is assumed to be in the order of 70 mm on the tunnel ceiling and in the elevator and skip shafts and 40 mm shotcrete is applied on the tunnel walls and in investigation tunnels and ventilation shafts. The shotcrete is assumed to contain about 450 kg cement and 75 kg steel fibres for reinforcement per m^3. The amount of shotcrete is given in Table 8-4

The shotcrete is low alkali cement but the final composition is not presently available, but will be specified in the final version of the report.

Grout holes

The amount of grouting needed around the other rock cavities (per metre cavity) is presently estimated to be similar to the amounts estimated for the deposition tunnels, see Section 7.2.11.

Stray materials

The amount of stray materials left in other rock cavities is presently estimated to be similar to the amounts left in the deposition tunnels, see Section 7.2.11.

Table 8-3. Examples of recipes for low alkali paste and mortar grouts for anchoring of rock bolts.

Component	Amount (kg/m³) Low alkali paste grout	Low alkali mortar grout
White cement	596	310
Silica fume	255	103
Limestone (0–0.8 mm)	-	1238
Water	696	412
Super plasticizer	2	2

Table 8-4. Estimated amounts of construction material left in other repository cavities after repository closure.

	Rock bolts (kg/m)		Shotcrete (kg/m)			Grout holes (kg/m)
	steel	grout	concrete	cement	steel fibres	grout
Ramp	60	30	3600	700	100	32[1)]
Central area	130	65	5400	1000	170	22[1)]
Transport tunnels	60	30	3600	700	100	32[1)]
Main tunnels	80	40	4400	800	140	12[1)]

1) this value assumes that 50% of injected grout stay in the grout holes.

9 Plugs

9.1 General

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

Operating plugs

The backfilled deposition tunnel needs to be sealed awaiting the backfilling of the main tunnel. The operating plug is sized to prevent water flow and to be strong enough to withstand the combined pressure from groundwater and the swelling of the bentonite. 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 considered 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. 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.

The general design of the plug is assumed to be the same in tunnels excavated by boring and blasting as in mechanically excavated tunnels (TBM).

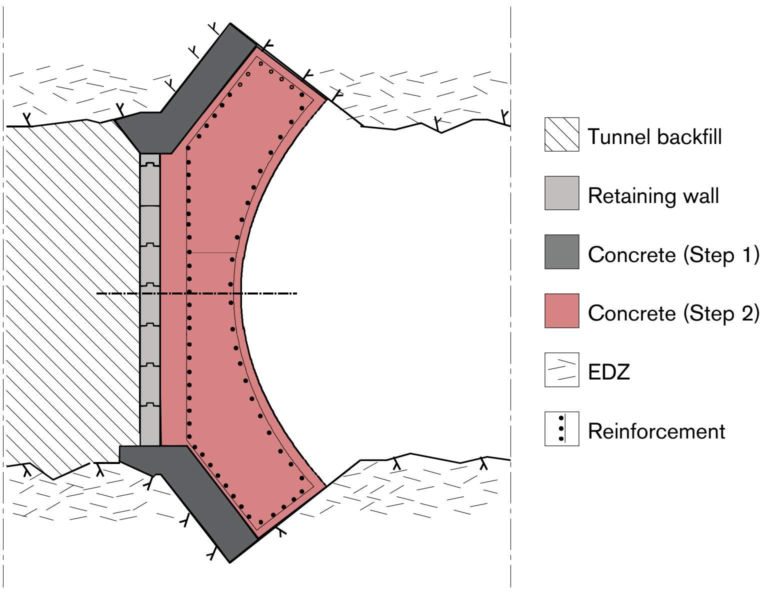

Figure 9-1. *The design of the operational plug, schematic drawing.*

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	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 plug. 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 (pressure 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 seals in the deposition tunnels.

	Blasted deposition tunnel	Bored deposition tunnel
Retaining wall		
Height or diameter (m)	5.5	∅ 6.0–6.5
Width (m)	5.5	-
Thickness (m)	0.3	0.3
Slot		
Depth (m)	1.0±0.5	1.0±0.5
Main plug body		
Height or diameter (m)	5.5 (+0.5/–0)	∅ 6.0–6.5
Width (m)	5.5 (+0.5/–0)	-
Thickness (m)	1.2–1.4	1.2–1.4

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 about 6 m^3.

The main body of the plug is about 1.2–1.4 m thick and has a total volume of about 50–60 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 is 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 7 MPa for depths varying between 400 and 700 m. The swelling pressure of the backfill is designed to be at least 0.1 MPa, and can be a coupled of 0.1 MPa higher. 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 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 n the final part of the backfilled tunnel. A maximum increase to a swelling pressure of 1 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 metre reinforcement bars with the diameter 25 mm and 200 metre with the diameter 16 mm, and in addition 480 metre U-links with the diameter 12 mm.

The plug has a total volume of 50–60 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: 1200 metre reinforcement bars with the diameter 25 mm and 80 metre with the diameter 16 mm. Other components in the plug are about 60 metre contact grouting tubes (type: Fuko) and 200 m cooling tubes made of steel with a diameter of 20 mm. 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 pH cement is in progress but is presently not available.

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 can 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. 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 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. An important sealing criterion is that the plug 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 (clay).

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 upper ends of deep and steeply oriented boreholes need to be sealed by materials that can sustain the swelling pressure of the major part of the plug and offer resistance to external mechanical impact like intrusion, erosion and glaciation.

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.

10.2 Variables

12.2.1 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.

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 (including any radionuclides) in time and space in backfill in boreholes. This variable also includes material sorbed to the surface.
Temperature	Temperature as a function of time and space in boreholes.
Hydro variables (pressure and flows)	Flows and pressures of water and gas as a function of time and space in boreholes.
Stress state	Stress state as a function of time and space in backfill in boreholes.
Water composition	Composition of the water (including any radionuclides and dissolved gases) in time and space in backfill in boreholes.

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.

The position, direction, length and diameter of each drilled borehole is documented in the 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 site 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 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 1000 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 – content and composition

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 moraine from the site.
- 3–50 m, well 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 moraine 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.

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 1600 to 2000 kg/m^3 (2008 to 2260 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.

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

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.

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

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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	

Table 1-1. Continued.

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	4042.1
	Overall Assembly Length – With Fuel Box	mm	4422.00
	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	3710
	Irradiation Length Increase	mm	15
	Design Burnup	MWd/tU	43000
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	
Rods	Number of Rods – Total		96
	Number of Fuel Rods		96
	Normal Fuel Rod Length		
	Supporting Fuel Rod Length	mm	4041
	Spacer Rod Length	mm	4004.5
	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	

Table 1-2. Continued.

Area	Description	Unit	Value
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
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