Technical Report

TR-12-08

Closure of the Spent Fuel Repository in Forsmark

Studies of alternative concepts for sealing of ramp, shafts and investigation boreholes

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Summary

In March 2011, SKB submitted applications under the Nuclear Activities Act and the Environmental Code for the construction and operation of a final repository for spent nuclear fuel in Forsmark. An important supporting document for the application under the Nuclear Activities Act was the SR-Site safety assessment. As a part of the work with the application and as background material for SR-Site, SKB prepared production reports, including the closure production report. The closure production report presented definitions, requirements and design premises, a reference design and the initial state for repository closure.

SR-Site evaluated the reference design and related design premises that were presented in the closure production report. SR-Site thereby concluded that the design premises on which the reference design were based are adequate. Relaxing the requirements would require additional sensitivity analyses focusing on the hydraulic properties of the access, main and transport tunnels. SR-Site further concluded that the reference design could likely be simplified without violating the current design premises. Furthermore, additional simplifications could probably be made if the design premises could be revised. This has been studied in the project *Closure – concept studies*, whose results are presented in this report.

SR-Site also evaluated the reference design for investigation boreholes that is presented in the production report. The evaluation showed that the impact of improper borehole seals is very moderate.

Further, SR-Site concludes that the current design premises are appropriate but possibly too strict, since even open boreholes seem to have a limited impact on the groundwater flow in the repository. Since it might be difficult to inspect the outcome of the current design of borehole sealing, it could be of interest to assess whether a solution that may result in higher effective permeability of the borehole seals would provide sufficiently good sealing. Such a solution, which could be based on crushed rock with the right grain size distribution, might also be more robust to control and verify with respect to long-term durability. However, relaxing the design premises in this way would require additional sensitivity analyses. Further, the assessment in SR-Site indicates that the reference design is appropriate for the purpose. However, if the the design premises are relaxed, more robust designs might be worth investigating. This has been studied and the results are presented in this report.

Research and development specifically focused on technology for repository closure has not yet been carried out. On the other hand, SKB and other organisations have for many years studied and conducted considerable research on backfilling and sealing of deposition tunnels, including full-scale tests.

SKB has also developed and tested technology for sealing of investigation boreholes. Experience and results from these efforts comprise an important basis for this project.

The work within the project has included the following main activities:

- Identification and presentation of alternative designs for sealing of ramp, shafts and boreholes.
- Discussion and choice of alternative designs for further studies.
- Hydromodelling of a number of alternatives for closure of the final repository in Forsmark.
- Safety evaluation of chosen alternatives.
- Presentation of proposal for revised design premises and new reference design for sealing of ramp, shafts and boreholes.
- Proposals for further technology development.

The work has focused on sealing of shafts, ramp and investigation boreholes. Alternatives for top sealing and sealing of the central area have not been studied, since their impact on the flow through the repository is judged to be marginal. Nor have alternative concepts for sealing of main and transport tunnels been developed, since it is believed that filling with blocks and pellets of swelling clay is the only alternative that ensures sufficiently low hydraulic conductivity.

The following requirements and premises have been taken into consideration in the work:

- The average hydraulic conductivity (the integrated effective connected hydraulic conductivity) of the backfill in tunnels, ramp and shafts and in the EDZ surrounding them must be lower than 10^{-8} m/s. This value need not be upheld in sections where e.g. the tunnel or ramp passes highly transmissive zones.
- The top seal may not be deeper than 100 metres above repository depth.
- It must be possible to fabricate, install and inspect the closure with high reliability.
- The sealing and methods for fabrication or preparation, inspection and installation must be cost-effective.
- When choosing closure materials and methods for preparation and installation of the closure, conservation of energy and resources must be taken into account.

The following alternatives have been studied for sealing of ramp and shafts:

Alternative 1A – roughly corresponds to the reference design in the application. From repository level up to 200 m below ground level, the ramp is filled with swelling clay, either in the form of blocks and pellets or only pellets. The fill is given a density and a swelling mineral content that gives it a hydraulic conductivity of 10^{-8} m/s or lower after homogenization and water saturation. Between 200 and 50 m below ground level, the ramp is filled with crushed rock. The shafts are also filled with swelling clay between the repository level and up to 200 m below ground level.

Alternative 1B – the ramp is sealed in the same way as in Alternative 1A. The shafts are filled with crushed rock from the repository level to 50 m below ground level.

Alternative 2A – the ramp is filled with swelling clay in the form of blocks and pellets or only pellets from the repository level and 100 m upward. Between 100 m above the repository level and 50 m below ground level, the ramp is filled with crushed rock. The uppermost part of the ramp is filled with stone blocks of varying size; the fill is then injected with concrete grout. The shafts are also filled with swelling clay from the repository level and 100 m upward and with crushed rock up to 50 m below ground level. The uppermost part is filled with coarser rock material.

Alternative 2B– the ramp is sealed in the same way as in Alternative 2A. The shafts are filled with crushed rock that has been optimised for low hydraulic conductivity, from repository level all the way up to the top seal.

Alternative 3 – In this alternative, hydraulically tight plugs are placed at strategic locations along the ramp and the shafts are filled with crushed rock. The idea behind this alternative is to achieve a cost-effective solution while meeting the requirement on axial conductivity across the whole ramp.

Two alternatives have been studied for sealing of boreholes:

Alternative B1 – In this alternative, the boreholes are sealed with perforated copper tubes filled with highly compacted smectite-rich clay. The alternative is the same as the reference design in the applications.

Alternative B2 – In this alternative, the investigation boreholes are filled with crushed rock that has been optimised for low hydraulic conductivity.

In order to assess the long-term safety of these alternatives compared with the reference design in the applications, hydrogeological groundwater flow modelling has been conducted. The modelling is based on the hydrogeological models developed for Forsmark within SR-Site. The modelling has included Block 1, i.e. the part of the repository that includes the ramp and the shafts located close to the central area. Block 1 contains about one-third of all deposition positions and 14 investigation holes (8 cored boreholes and 6 percussion boreholes). The safety evaluation includes a sensitivity analysis where the effects of different hydraulic properties for the borehole seal have been studied. Two climate scenarios have been studied: temperate climate shortly after closure, and glacial conditions when the ice front is located roughly above the middle of the repository.

Modelling results and comparisons with the results in SR-Site show that the properties of the sealing in the ramp, the shafts and the EDZ have little impact on long-term safety. Groundwater and transport modelling show that the few particles that leave a deposition position reach the surface primarily via deformation zones and only to a limited extent via ramp and shafts.

Similar results are obtained for the investigation holes. Only when the hydraulic conductivity is greater than 10^{-6} m/s can any effect be seen, and neither is the penetration of oxygen down to the repository significantly affected.

In the hydrogeological groundwater flow modelling, two climate situations are considered: one during the temperate period soon after complete closure and re-saturation of the repository, and one during the glacial period when the ice front is located roughly above the middle of the repository (ice front location II) The temperate climate situation is believed to be quite plausible, and the situation with ice front location II is representing somewhat of a worst case scenario.

The analyses and assessments that have been performed within the project show that the reference design can be simplified and that sealing can be done cost-effectively without compromising safety. The following *reference design* is proposed for sealing of ramp and shafts:

> The ramp is filled with swelling clay in the form of blocks and pellets or only pellets from the repository level and 100 m upward. Between 100 m above the repository level and 50 m below ground level, the ramp is filled with crushed rock. The uppermost part of the ramp is filled with stone blocks of varying size. The fill is then injected with concrete grout. The shafts are filled with crushed rock that has been optimised for low hydraulic conductivity, from repository level all the way up to the top seal.

This concept is judged to meet the requirements on long-term safety. At the same time, the concept is judged to be the most cost-effective solution and the alternative that requires the least transport and thereby has the least environmental impact. Installing crushed rock instead of swelling clay in the shafts is also judged to be more robust and entail lower risks in production and installation of the seal. This needs to be verified by further studies and tests, however.

Further, the results of analyses and evaluations show that the design premises with respect to long-term safety for sealing of investigation holes can be relaxed. The following is proposed as a new *design premise*:

> The resulting hydraulic conductivity over the length of the borehole shall be lower than 10^{-6} m/s.

The results from analyses and assessments do not support proposing a new reference design for sealing of investigation boreholes. The most important reason is that the simpler alternatives that could satisfy the new requirements, for example sealing the investigation boreholes with crushed rock that has been optimised for low hydraulic conductivity or plugging the holes with concrete, are not as technologically mature as the current reference design. Further studies are needed before it is possible to change the reference design, including tests and trials of alternative designs.

The report mentions a number of issues that require further in-depth studies and/or continued technology development. The most important issues are:

- Description of initial state.
- Methodology for showing and verifying that proposed solutions meet stipulated requirements.
- Handling of water, including the inflow of water to those parts of the ramp where bentonite fill has been installed and handling of water coming from the part of the ramp that has not yet been filled.
- Technology development and demonstration for sealing of shafts with crushed rock and with bentonite.
- Technology development for borehole sealing, including showing how crushed rock can be installed and inspected.
- Detailed plan for sealing of the repository level, including preliminary plug positions. This might affect the layout of the final repository on repository level.
- Plugs: design to meet the stipulated requirements and ensure the long-term function of the concrete plugs.
- Rock support: to what extent should shotcrete be removed before sealing is done, considering e.g. the working environment.

Contents

1 Introduction and background

In March 2011, SKB submitted applications under the Nuclear Activities Act and the Environmental Code for the construction and operation of a final repository for spent nuclear fuel in Forsmark. An important supporting document for the application under the Nuclear Activities Act was the SR-Site safety assessment. As a part of the work with the application and as background material for SR-Site, SKB prepared production reports for fuel, canister, buffer, backfilling, closure and underground openings. The closure production report, *Design, production and initial state of the closure*, presents definitions, requirements and design premises, the reference design and the initial state of the closure (SKB 2010b).

The closure production line includes materials for and execution of sealing of all underground openings except the deposition tunnels and sealing of investigation boreholes. With the exception of certain investigation boreholes, sealing and closure will not begin until all spent fuel has been deposited. Detailed design and execution therefore still lie more than 50 years in the future.

Research and development specifically related to technology for repository closure has not yet been carried out. On the other hand, SKB and other organisations have for many years studied and conducted considerable research on backfilling and sealing of deposition tunnels, including full-scale tests. SKB has also developed and tested technology for sealing of investigation boreholes. Experience and results from these efforts comprise an important basis for this project.

The closure is one of the barriers in the KBS-3 repository. Its purpose is to prevent the flow of groundwater in tunnels, ramp and shafts, as well as in boreholes. Sealing of the uppermost parts of the ramp and shafts is supposed to prevent inadvertent intrusion in the repository. The closure must not adversely affect the function of the other barriers to any appreciable degree. The closure in the main tunnels is supposed to prevent the backfill in connecting deposition tunnels from losing its barrier function by expanding or being transported out of the tunnels. The closure in each underground opening shall be executed so that the closure in adjacent underground openings is kept in place.

1.1 Current reference design

As a basis for the safety assessment SR-Site and based on stipulated requirements and design premises, SKB has established the following reference design for closure/sealing of the different parts of the final repository (SKB 2010b):

- *Main and transport tunnels as well as ramp and shafts up to top seal*: backfilling with compacted blocks and pellets of swelling clay, according to the same concept as for backfilling of deposition tunnels. On passage of water-conducting zones, it may be necessary to install plugs. Plugs may also be needed where different closure materials border on each other, for example where the transport tunnels connect to the central area. In the current phase of technology development, the same conceptual reference design applies to plugs for sealing of main and transport tunnels as to plugs in deposition tunnels.
- *The central area*: backfilling with crushed rock that is compacted.
- *The top seal*, i.e. the upper part of ramp and shafts (from the –200 metre level up to –50 metres): backfilling with crushed rock that is compacted. To obstruct intrusion in the repository, the uppermost parts (from about –50 metres up to the ground surface) are sealed with coarser rock material.
- *Investigation boreholes*: perforated copper tubes filled with highly compacted bentonite. In sections where the borehole passes water-conducting zones, the clay may erode. These passages are therefore filled with quartz-based concrete, which is permeable and resistant to erosion. The uppermost part of the borehole is supposed to resist the clay's swelling pressure and withstand mechanical stresses. This part is therefore sealed with cylindrical rock plugs in combination with in situ-cast concrete plugs and well compacted till.

1.2 Feedback from SR-Site

1.2.1 Sealing of main tunnels, transport tunnels, access tunnels, shaft and central area

SR-Site evaluated the reference design that is presented in the closure production report and related design premises. It is concluded in section 15.5.19 in the SR-Site report (SKB 2011) that the design premises according to SKB (2009) are adequate. Further relaxing the requirements would require additional sensitivity analyses focusing on the hydraulic properties of the access, main and transport tunnels. SR-Site further concludes that the reference design could likely be simplified without violating the current design premises. Furthermore, additional simplifications could probably be made if the design premises could be revised. This has been studied in the project *Closure – concept studies* and the results are presented in this report.

1.2.2 Sealing of boreholes

SR-Site also evaluated the reference design for boreholes that is presented in the closure production report and related design premises. In the SR-Site report, section 15.5.20, the impact of an open borehole on the groundwater flow in the repository and the surrounding rock was studied. In the analyses, boreholes were introduced at various locations in the hydrogeological model that was used for the analyses of the temperate period in SR-Site (Joyce et al. 2010). The analyses showed that the impact of improper seals of the boreholes is very moderate. The evaluation also showed that the reference design of the borehole seals will perform as intended. Clearly, the bentonite may be lost in sections intersecting highly flowing fractures, but in the reference design there is no bentonite in such sections.. The main remaining issue is that it is difficult to inspect the quality of the seals after installation. Therefore their performance after installation, saturation and homogenisation needs to be demonstrated. A loss of bentonite in the range of a few metres in the seals will lead to a total loss of performance in that section, but the rest of the seal will be virtually unaffected. The function of the seal is not to hinder flow in the intersecting fractures, but to hinder flow along the borehole, so loss of function over a few metres is not a significant consideration.

In summary, SR-Site concludes that the current design premises are adequate. However, it may be argued that the current design premises for the borehole seals are too strict, since even open boreholes seem to have a limited impact on the flow. Since it might be difficult to inspect the outcome of the current design of borehole sealing, it could be of interest to assess whether a solution that may result in higher effective permeability of the borehole seals would provide sufficiently good protection. Such a solution, which could be based on crushed rock with the right grain size distribution, might also be more robust to control and verify with respect to long-term durability. However, relaxing the design premises in this way would require additional sensitivity analyses. Further, the assessment in SR-Site indicates that the reference design is appropriate for the purpose. However, if the the design premises are relaxed, more robust designs might be worth investigating. This has been studied and the results of completed analyses are presented in Chapter 5.

1.3 Scope and purpose of work

The project has focused on sealing of shafts, ramp and investigation boreholes. Different alternatives have been proposed for these closures. Alternatives for the top seal have not been studied since its impact on the flow through the repository is judged to be marginal. Nor have alternative concepts for sealing of main and transport tunnels been developed, since it is believed that filling with high density high quality bentonite blocks and pellets is the only alternative that ensures sufficiently low hydraulic conductivity. Alternatives for sealing of the central area have not been studied, since its impact on the flow through the repository is judged to be marginal and because solutions that provide low hydraulic conductivity entail practical problems and high costs.

1.4 Requirements and design premises

As far as requirements and design premises are concerned, the work has been based on the closure production report (SKB 2010b). See also Appendix A, which presents requirements and design premises for closure as they were formulated at the time of SKB's application (March 2011).

It should be noted that the requirements on sealing of main and transport tunnels as well as ramp and shafts are much less strict than the requirements on sealing of the deposition tunnels. This includes both the hydraulic conductivity (10^{-8} m/s for sealing vs. 10^{-10} m/s for backfilling) and the requirement that the backfill should serve as a restraint for the buffer; there is naturally no such requirement on the closure for tunnels, ramp and shafts. Despite this, the reference design for sealing of these underground openings is the same as for backfilling of the deposition tunnels. This means that the reference design for sealing with precompacted bentonite blocks is "overstrong". However, this overstrong alternative was not analysed in SR-Site; there it was assumed that the sealed tunnels, ramp and shafts had a hydraulic conductivity of 10^{-8} m/s, i.e. according to the stipulated requirements.

In the work of arriving at alternative sealing concepts, the following requirements and premises have been taken into consideration (the description of the design premises in the following is abridged; complete texts are provided in Appendix A):

- The closure must prevent the formation of water-conducting channels between the repository and the surface. The average hydraulic conductivity (the integrated effective connected hydraulic conductivity) of the backfill in tunnels, ramp and shafts and in the EDZ surrounding them must be lower than 10^{-8} m/s. This value need not be upheld in sections where e.g. the tunnel or ramp passes highly transmissive zones (Requirement SRCAN178).
- The top seal may not be deeper than 100 metres above repository depth (Requirement SRCAN179).
- The only function of the closure of the cavities in the central area is to occupy the space with no other design premise than to prevent substantial convergence and subsidence of the surrounding rock. Thus, there are no restrictions in the central area with regard to hydraulic conductivity (Requirement DRCL27).
- The size and distribution of the water inflow is obtained from SR-Site's hydromodels.
- It must be possible to fabricate, install and inspect the closure with high reliability (Requirement SSCL23, SSCL24).
- The sealing and methods for fabrication or preparation, inspection and installation must be cost-effective (Requirement SSCL34).
- When choosing closure materials and methods for preparation and installation of the closure, conservation of energy and resources must be taken into account (Requirement SSCL40).

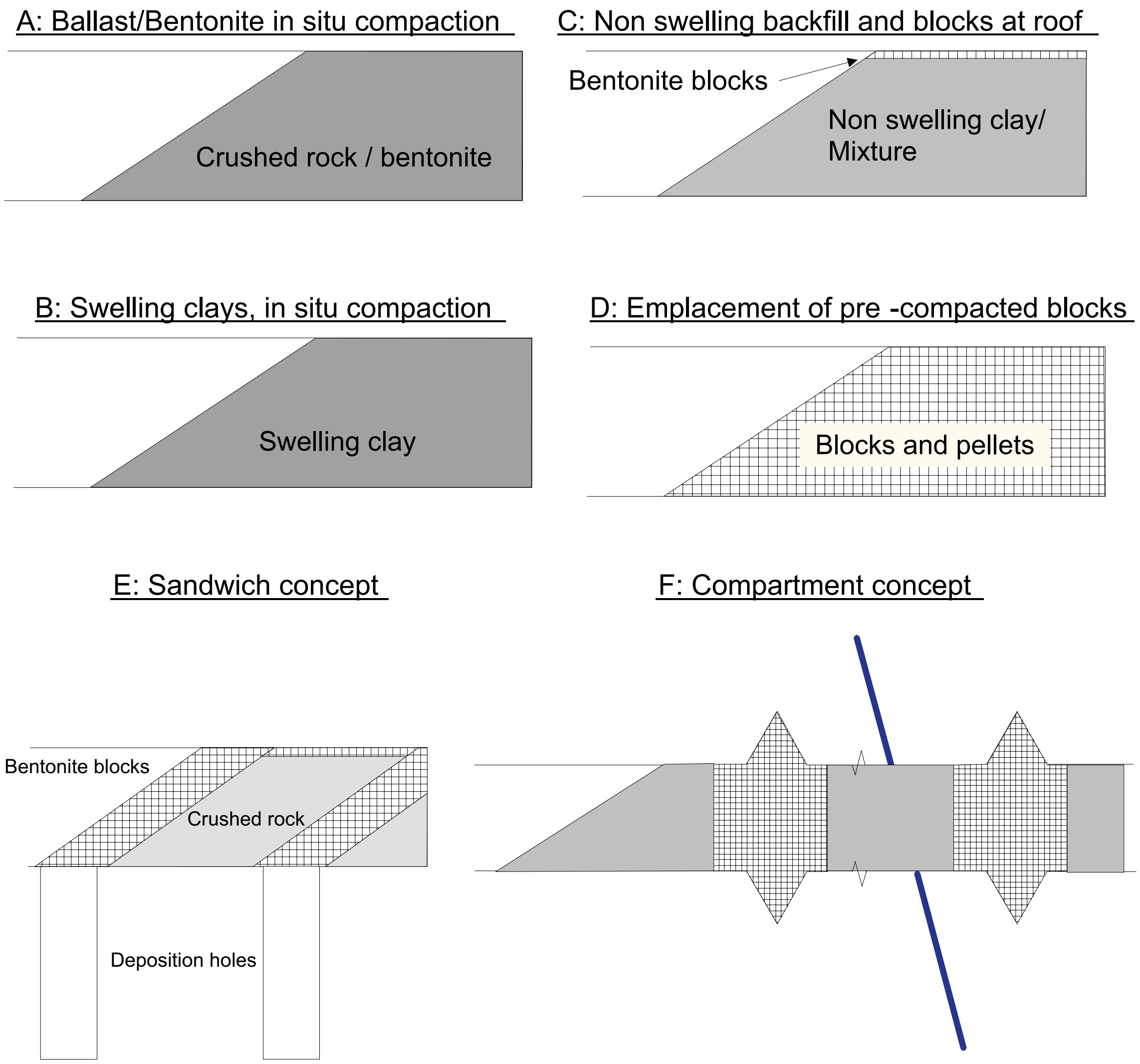
The results of the hydromodelling presented in Chapter 5 comprise a basis for evaluating and possibly updating requirements and design premises for long-term safety.

2 Studied alternatives for ramp and shafts

2.1 Background

SKB has conducted extensive studies, trials and tests for backfilling of deposition tunnels, see SKB (2010a). For a long time the main alternative was to backfill the deposition tunnels with a mixture of bentonite clay and crushed rock. For example, a mixture consisting of 15 weight percent MX-80 and 85 weight percent crushed rock was analysed in the safety assessment SR 97. Other underground openings were then assumed to be backfilled and sealed with the same type of material. There was therefore no reason to conduct special studies of closure of other openings in the repository.

Prior to SR-Can and the choice of materials and method for backfilling of deposition tunnels, SKB evaluated a number of backfilling concepts (Gunnarsson et al. 2004), see Figure 2-1.



A: Ballast/Bentonite in situ compaction

C: Non swelling backfill and blocks at roof

B: Swelling clays, in situ compaction

D: Emplacement of pre -compacted blocks

E: Sandwich concept

F: Compartment concept

Figure 2-1. Backfilling concept for deposition tunnels studied prior to SR-Can (Gunnarsson et al. 2004).

The result was a recommendation to employ backfilling with pre-compacted blocks and pellets. The method was judged to have advantages, since it was possible to obtain a backfill with a high average density (Gunnarrsson et al. 2006).Thus, two concepts for backfilling of the deposition tunnels were analysed in SR-Can (SKB 2006):

1. The tunnel is filled with pre-compacted blocks. The space between the rock and the blocks is filled with bentonite pellets. The blocks are made of a mixture of bentonite of buffer quality (30 weight percent) and crushed rock (70 weight percent, particle size max. 5 mm). The uppermost metre of the deposition hole is backfilled with the same material as the tunnel.
2. The tunnel is filled with pre-compacted blocks. The space between the rock and the blocks is filled with bentonite pellets. The blocks are made of Friedland clay, a naturally swelling clay with approximately 50 percent smectite. The uppermost metre of the deposition hole is filled with bentonite blocks of the same material and with the same dimensions as the buffer blocks placed on top of the canister.

The deposition tunnels were sealed with a plug made of low-pH concrete.

Others tunnels and shafts were assumed to be backfilled/sealed according to alternative 1, i.e. pre-compacted blocks of crushed rock and bentonite. No alternatives were studied.

2.2 Closure Alternative 1A

2.2.1 General description

Alternative 1A roughly corresponds to the reference design in the application. Plugs are installed in shaft and ramp to handle inflowing water; see section 6.2.2. The idea behind alternative 1A is to seal the repository so that shafts and ramp are as hydraulically tight as is practically possible where they pass through tight rock, but without evaluating requirements on other environmental impact, flexibility or cost-effectiveness. The rock down to 200 m below ground level is criss-crossed by water-bearing fractures, so the hydraulically tight sealing begins at this level. The parts of shafts and ramp that are to be hydraulically tight are filled with bentonite clay with low hydraulic conductivity that generates sufficiently high swelling pressure to ensure good contact with the roof and walls of the tunnels.

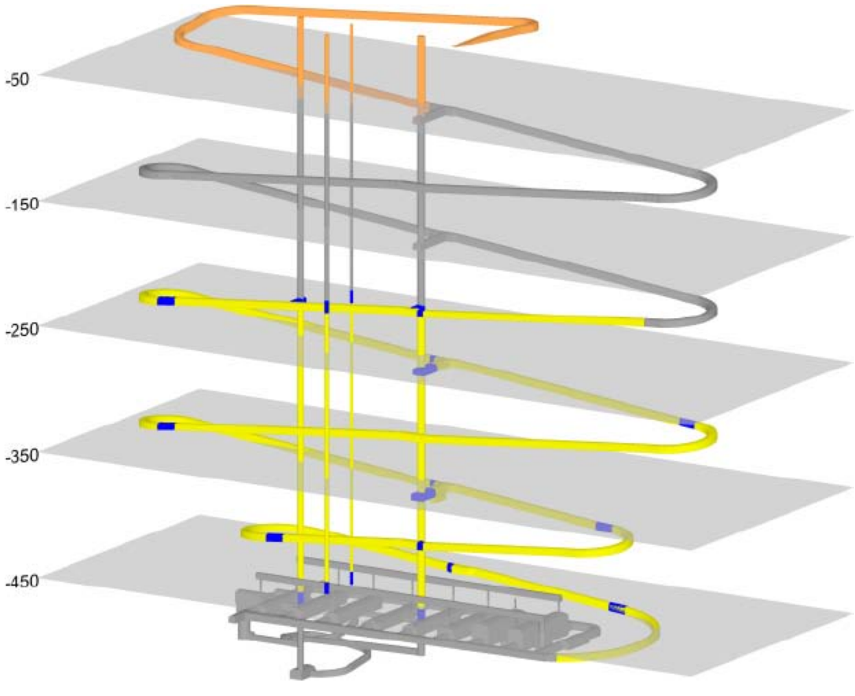


Figure 2-2. Alternative 1A. Grey colour represents crushed rock, yellow bentonite-filled sections, blue installation plugs of concrete and brown top seal.

2.2.2 Ramp

From repository level up to 200 m below ground level, the ramp is filled with swelling clay, either in the form of blocks and pellets or only pellets. The fill is given a density and a swelling mineral content that gives it a hydraulic conductivity of 10^{-8} m/s or lower after homogenization and water saturation.

Between 200 and 50 m below ground level, the ramp is filled with crushed rock. The different closure materials are designed so that leaching is minimised. Several filter layers between the different closure materials may be needed. It is assumed that the EDZ in the sections sealed with swelling clay has a hydraulic conductivity lower than 10^{-8} m/s. The top seal is described in section 3.3.

The ramp begins to be backfilled after the central area has been filled and a plug has been installed. The work proceeds in steps until the ramp has been backfilled to the extent that the cumulative water flow to the backfilled section risks causing practical problems. A mechanical and hydraulic plug that isolates the filled section is installed and the next section is backfilled. Sections with high water flows can be isolated with a hydraulic/mechanical plug on either side. The space between the plugs is filled with crushed rock. This is further described in section 6.2.2.

2.2.3 Shaft

The shafts are also filled with swelling clay between the repository level and up to 200 m below ground level. From this level, the shafts are filled with crushed rock up to 50 m below ground level. The uppermost part is sealed with large rock blocks that are trimmed to fit tightly to each other. The different fill materials are designed in the same way as for the ramp. The conditions for installation and thereby the installation method differ between shafts and ramp, so that for example it may be more optimal to install bentonite blocks and pellets in the ramp and only pellets in shafts. It is assumed that the EDZ in the sections sealed with swelling clay has a hydraulic conductivity lower than 10^{-8} m/s.

2.3 Closure Alternative 1B

2.3.1 General description

The idea is the same as in alternative 1A, to seal shafts and ramp between repository level and 200 m below ground level with material with low hydraulic conductivity. The difference is that the shafts are filled with crushed rock with a grain size distribution that provides low hydraulic conductivity. The requirement stated for long-term safety is that the hydraulic conductivity must be lower than 10^{-8} m/s. Laboratory tests have shown that this can be achieved with good margin (Pusch 2008).

2.3.2 Ramp

Sealed in the same way as alternative 1A.

2.3.3 Shaft

The shafts are filled with crushed rock from the repository level to 50 m below ground level. The rock is crushed and ground so that the grain size distribution corresponds to a Fuller grading curve. It is important that the shaft be filled without the crushed rock being separated, that it is installed at the right water ratio and that it is compacted to sufficiently high density.

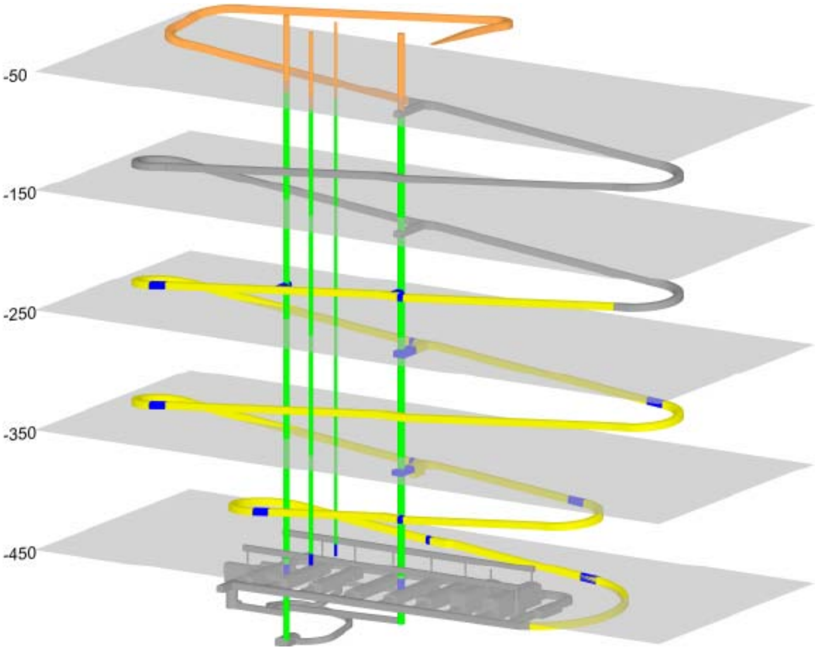


Figure 2-3. *Alternative 1B. Grey colour represents crushed rock, yellow bentonite-filled sections, green crushed rock that has been optimised for low hydraulic conductivity, blue installation plugs of concrete and brown top seal.*

2.4 Closure Alternative 2A

2.4.1 General description

This alternative is based on the assumption that it is sufficient to seal the lowermost part of shafts, ramp and investigation boreholes and that the flow resistance above this level has no impact on long-term safety. If this assumption can be confirmed, this alternative also meets the requirements on flexibility and cost-effectiveness.

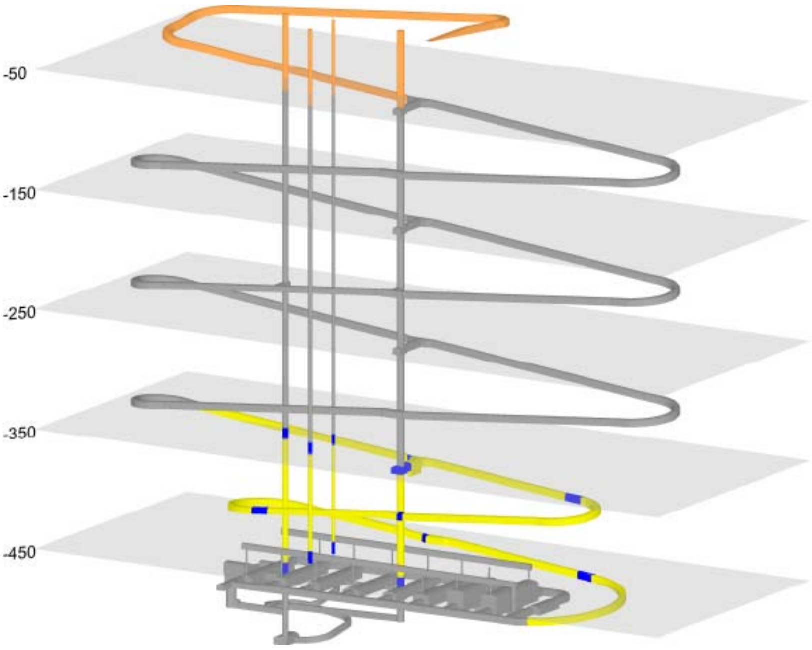


Figure 2-4. *Alternative 2A. Grey colour represents crushed rock, yellow bentonite-filled sections, blue installation plugs of concrete and brown top seal.*

2.4.2 Ramp

The ramp is filled with swelling clay up to 100 m above repository level either in the form of blocks and pellets or only pellets. The fill is given a density and a swelling mineral content that gives it a hydraulic conductivity of 10^{-8} m/s or lower after homogenization and water saturation. Between 100 m above the repository level and 50 m below ground level, the ramp is filled with crushed rock. The different closure materials are designed so that leaching is minimised. Plugs are installed between the ramp and the central area and between sections filled with swelling clay and crushed rock. Several filter layers between the different fill materials may be needed. It is assumed that the EDZ in the sections sealed with swelling clay has a hydraulic conductivity lower than 10^{-8} m/s. The top seal is described in section 3.3.

2.4.3 Shaft

The shafts are also filled with swelling clay up to 100 m above repository level. Above that the shafts are filled with crushed rock up to 50 m below ground level, and in the uppermost part with coarser rock material. The different fill materials are designed in the same way as for the ramp. The installation method differs between shafts and ramp, so that for example it may be more optimal to install blocks and pellets in the ramp and only pellets in shafts.

2.5 Closure Alternative 2B

2.5.1 General description

The lower part of the ramp is sealed with swelling clay between the repository level and 100 metres above the repository level, while the shafts are filled with crushed rock that has been optimised for low conductivity all the way down to the repository level. The idea behind this alternative, not to backfill any part of the shafts with bentonite, is that it is judged advantageous with respect to execution and costs and that crushed rock is assumed to be more durable than eroding bentonite. Since the requirements on hydraulic conductivity can be met with crushed rock, this concept should meet the requirements on long-term safety.

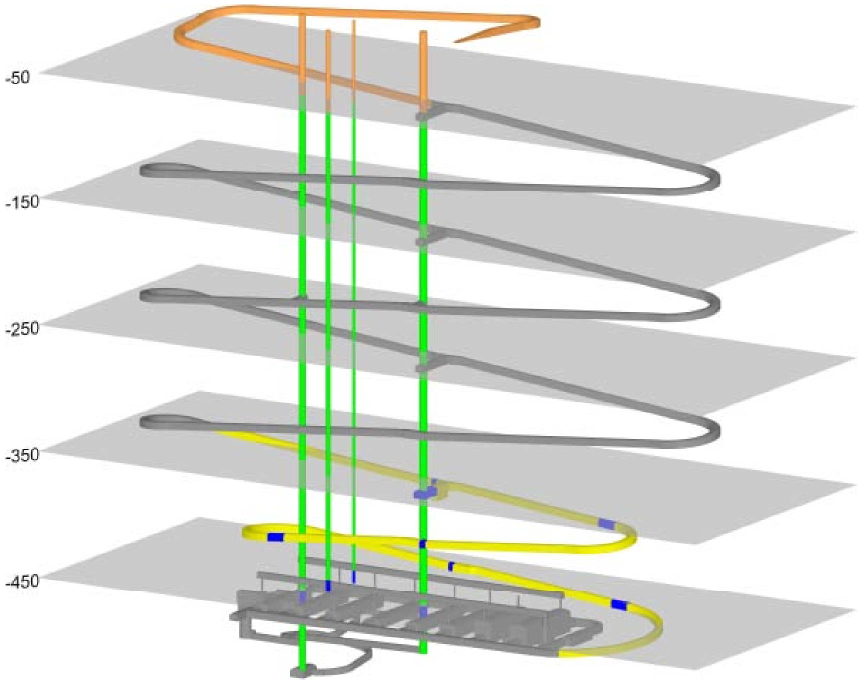


Figure 2-5. *Alternative 2B. Grey colour represents crushed rock, yellow bentonite-filled sections, green crushed rock that has been optimised for low hydraulic conductivity, blue installation plugs of concrete and brown top seal.*

2.5.2 Ramp

Sealed in the same way as Alternative 2A.

2.5.3 Shaft

The whole length of the shafts from the repository level up to the top seal is filled with crushed rock that has been optimised for low hydraulic conductivity. Since the central area is also filled with crushed rock, it is possible that no plug is needed between this and the shafts. It is assumed that the EDZ has a hydraulic conductivity lower than 10^{-8} m/s, at least up to 100 m above repository level.

2.6 Closure Alternative 3

In this alternative, hydraulically tight plugs are placed at strategic locations along the ramp and the shafts are filled with crushed rock. The idea behind this alternative is to achieve a cost-effective solution while meeting the requirement on axial conductivity across the whole ramp. The EDZ only needs to be removed in those positions where the plugs are placed. However, the assessment at this early stage is that the costs saved by filling a totally shorter length of the ramp with swelling clay do not outweigh the extra costs incurred due to the fact that the equivalent tunnel length needs to be excavated by controlled blasting and the fact that more concrete plugs need to be installed. Moreover, due to questions surrounding the long-term performance of the concrete, it is necessary to study what happens when the concrete has degraded to the point where the bentonite is no longer held in place. The same questions also exist for the other concepts that include swelling clays, but there the problems are more limited since there is only one place where swelling clay borders on a concrete plug and crushed rock.

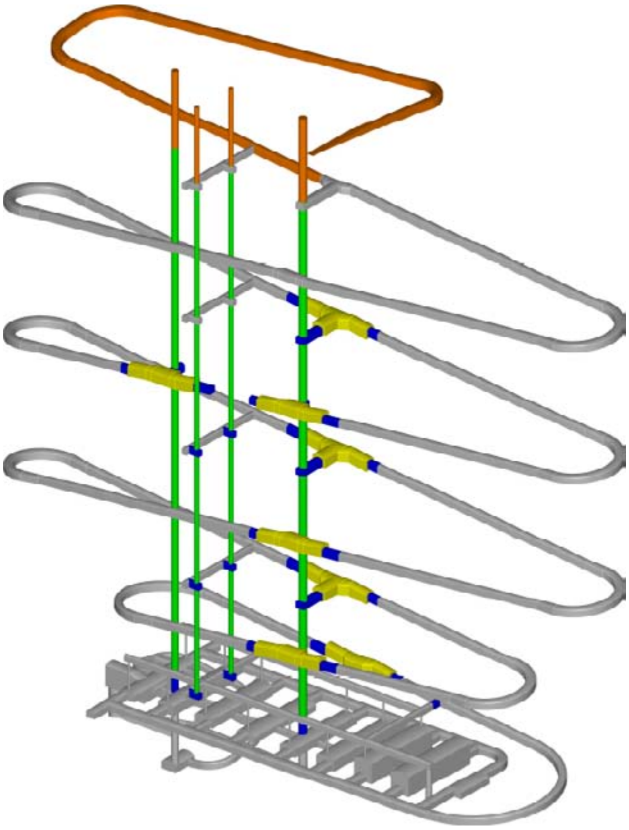


Figure 2-6. *Alternative 3. Grey colour represents crushed rock, yellow bentonite-filled sections, green crushed rock that has been optimised for low hydraulic conductivity, blue installation plugs of concrete and brown top seal.*

3 Sealing of other openings

3.1 Main and transport tunnels

The focus of the work reported has not been on the sealing of main and transport tunnels. In the reference design, these tunnels are sealed in a similar manner to the deposition tunnels. However, the requirements are less strict than on the backfill in the deposition tunnels (see section 1.4), which means that a lower density or a lower-quality material can be chosen. At this stage, priority has not been given to presenting alternatives for sealing of main and transport tunnels. Moreover, the design of the plugs in the deposition tunnels is based on the assumption that the main tunnels are filled with bentonite.

In the same way as for shafts and ramp, plugs presumably will have to be installed to handle inflowing water. According to the hydrogeological model calculations done for SR-Site, there will be sections with high water inflow mainly in transport tunnels, but also in main tunnels. In the transport tunnels, there is greater freedom to position plugs where suitable from a water handling viewpoint. In the main tunnels, there are fewer locations to position plugs due to all the connecting deposition tunnels. If it turns out that there are sections with relatively high water inflows, the positions of the deposition tunnels should be located so that it is possible to install plugs to handle inflowing water. This is a part of the optimisation of the repository.

3.2 The central area

The central area is sealed with crushed rock in the same way as in the reference design. The central area has a complex geometry, which imposes special demands on both execution and material. In order to keep the gap at the roof small, the crushed rock has to be compacted to minimise consolidation. If further studies show that tight contact against the roof is required, this means that swelling material has to be used in the uppermost part of the fill.

3.3 Top seal

Top sealing is done in the same way as in the reference design, whereby the uppermost part of the ramp is filled with stone blocks of varying size. The stone blocks are trimmed to fit tightly to each other. The fill is then injected with concrete grout.

4 Sealing of boreholes

4.1 Background

SKB has, in cooperation with Posiva, developed four concepts for plugging long and short boreholes (Pusch and Ramqvist 2007):

1. *The Basic concept* – the boreholes are plugged with perforated copper tubes filled with highly compacted smectite-rich clay (type MX-80). The concept was developed in the early 1980s, tested in the Stripa project and has been applied in the plugging of boreholes at SFR. A successful full-scale trial has been conducted by installing a clay plug in a borehole at a depth of about 500 metres in Olkiluoto.
2. *The Container concept* – a sealed tube containing compacted smectite-rich clay is placed in the borehole. The sealed tube isolates the clay from the borehole water during installation. When the tube is in the right position, the bottom is opened and the clay is pressed out. The concept entails that the clay becomes water-saturated and hardens faster than in the Basic concept. A prototype has been fabricated, but a full-scale trial has not been conducted.
3. *The Couronne concept* – a copper rod around which tightly fitting annular blocks of bentonite are fitted is placed in the borehole. The clay becomes water-saturated and hardens nearly as quickly as in the Container concept. The method has been tested in a trial.
4. *The Pellet concept* – highly compacted pellets of smectite-rich clay (of type MX-80) are blown directly into the borehole. The method has been used in several different applications. Nagra has conducted several tests in both upward- and downward-oriented boreholes.

In the development work on borehole sealing carried out to date, the design premise with regard to watertightness has been to restore the rock's natural hydraulic conductivity. In conjunction with SR-Site, the design premises were defined so that the resultant axial hydraulic conductivity over the length of the boreholes must be lower than 10^{-8} m/s. This makes it possible to look at materials that are not quite as watertight as highly compacted bentonite.

4.2 Alternative B1

This alternative corresponds to the *Basic concept* – the boreholes are plugged with perforated copper tubes filled with highly compacted smectite-rich clay (type MX-80). This alternative comprises the reference design in the application. The alternative has been developed and subjected to various tests (Pusch and Ramqvist 2007). The alternative has good prospects for meeting all requirements. Areas for further development are inspection and documentation of installed plugs and bentonite sections.

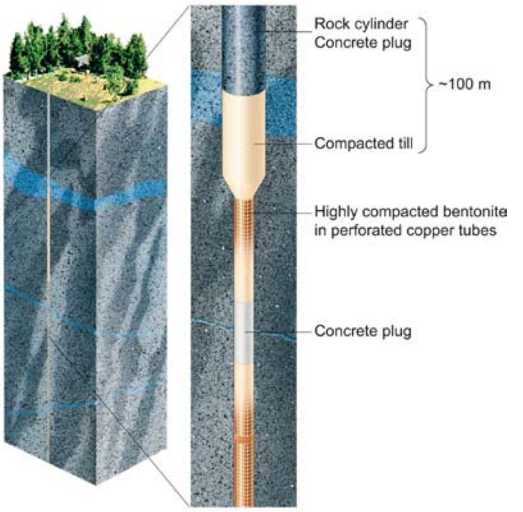


Figure 4-1. *Schematic illustration showing the reference design for sealing of investigation boreholes.*

4.3 Alternative B2

Based on the requirement that the hydraulic conductivity must be lower than 10^{-8} m/s, it should be possible to fill the investigation boreholes with crushed rock that has been optimised for low hydraulic conductivity. The requirement made for long-term safety is that the hydraulic conductivity must be lower than 10^{-8} m/s. Laboratory tests have shown that this can be achieved with good margin (Pusch 2008).

5 A safety assessment of the repository closure methodology

5.1 Background and introduction

In order to assess the long-term safety of alternatives to the reference design of the proposed repository, groundwater flow modelling has been conducted, including calculations of indicators typically used in safety assessments of repositories e.g. SR-Site (Joyce and Marsic 2012). The groundwater flow calculations are based on a conceptual model developed for SR-Site (SKB 2011) including e.g. the ramp, the shafts near the central area, a number of deposition tunnels, and about a third of the deposition holes. Using this nested approach, i.e. a CPM repository within a DFN model, it is necessary to limit the calculations to a smaller domain relative to the full repository in order to keep the computational workload within reasonable bounds. This means that some deposition tunnels, where the deposition holes are not represented explicitly, are instead represented as fracture structures to keep the connectivity to the lateral boundary. This is illustrated in Figure 5-1. In this conceptual model (denoted Block 1) a number of boreholes were added as well to study their potential impact on the long-term safety. In the calculations, some different design approaches are used and the hydraulic properties of the ramp, shafts, EDZ, and boreholes are varied.

The purpose of the modelling reported here is to investigate alternative designs of the repository closure and their influence on groundwater flow and transport in the repository area, particularly in proximity to the ramp and central area shafts. The influence of the ramp and shaft properties on the performance measures for the recharge and discharge pathways to the repository is considered. The recharge pathways are important for considering the flow of potentially dilute or oxygenated water to the repository. The discharge pathways are important for the transport of radionuclides to the surface.

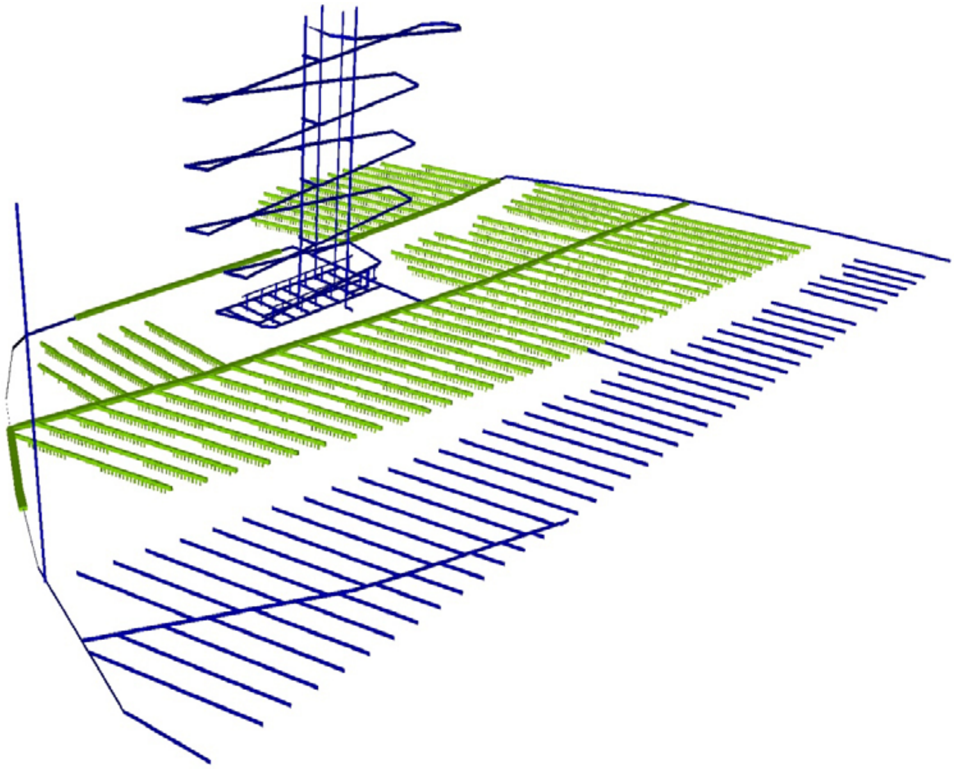


Figure 5-1. *SR-Site Forsmark block 1 repository-scale structures. The CPM structures are coloured green and the fracture structures are coloured blue. The blue tunnels (mainly deposition tunnels to the right and the lower part of the picture) are represented in Block 1 by fracture structures to reduce the computational effort but still keep the connectivity to the boundary.*

Another task reported here is a study of the influence of sealed investigation boreholes on groundwater flow and performance measures relevant for penetration of oxygen and radionuclide transport. A sensitivity analysis is performed where the hydraulic properties of the sealed boreholes are varied.

Due to the scope of this project, most cases are represented by a single realisation of the stochastically generated fractures. However, additional realisations are performed for some cases. Each realisation is then used as a platform for calculations of performance measures such as travel times and flow-related transport resistance for released particles from deposition holes, in addition to the Darcy flux at deposition holes, i.e. the same types of performance measures as were used in SR-Site (SKB 2011). For each performance measure, statistics are calculated, e.g. mean, median and a number of percentiles. Commonly, the performance measures for specific deposition holes vary significantly between realisations, but the ensemble statistics are quite similar between realisations. Even though it would be more convincing that statistically stable results had been obtained if more realisations could have been done within this project, it is not considered to be crucial for the results in this study.

Two climate situations are considered: one during the temperate period soon after complete closure and re-saturation of the repository, and one during the glacial period when the ice front is located roughly above the middle of the repository (ice front location II) (Joyce et al. 2010). The temperate climate situation is believed to be quite plausible, and the situation with ice front location II is representing somewhat of a worst case scenario.

For each case, a steady-state groundwater flow calculation is carried out using pressure boundary conditions and densities interpolated from the regional-scale model used in SR-Site, as described in (Joyce et al. 2010). Pressures and densities corresponding to 2000 AD for the temperate period and to glacial ice front location II for the glacial period are used in two separate simulations for each case. Following the flow calculations for each climate situation, particle tracking calculations are carried out.

Block 1 contains 1,994 deposition hole locations. As for SR-Site, three particles are released per deposition hole, corresponding to the Q1 (into a fracture intersecting a deposition hole), Q2 (into the EDZ) and Q3 (into the deposition tunnel, 1 m above the floor) release types. The particles are then tracked until they reach the boundaries of the model. Backward particle tracking is also carried out for the Q1 release locations to find the recharge pathways for the deposition holes, i.e. to track where the flow is coming from to each deposition hole. In SR-Site, the particles were further tracked in the site-scale model from the points where they exited the repository-scale blocks. However, for this study the particles will not be tracked further, so the performance measures will be truncated at the block boundaries. This should be sufficient, as the purpose of the study is to compare different variants where the variations are expected to have a fairly local effect, rather than to look at the absolute values of the performance measures. It is likely that a few particles will change their exit locations due to the altered variant, but for the ensemble of particles there will be a very small difference in exit locations since the pathways are controlled by the fractures, deterministic deformations zones, and the imposed boundary conditions.

5.2 Results

The results take the form of statistical summaries for the performance measures considered. The performance measures considered are travel time in the rock, t_r, equivalent Darcy Flux in the rock, U_r, and flow-related transport resistance in the rock, F_r.

Cumulative distribution function (CDF) plots show the cumulative fraction of particles as a function of performance measure value. They allow the distribution of performance measure values to be readily seen, including the tails of those distributions. Normalised plots filter out particles that do not start and particles that do not reach the boundaries of the model and then re-normalise the proportions to the range zero to one. Bar and whisker plots show side by side comparisons of statistical measures for each variant, including the median (red), 25th and 75th percentile (blue bar) and the 5th and 95th percentile (black "whiskers").

For each deposition hole there are three potential release paths denoted Q1, Q2, and Q3 in the model. Q1 represents release from the deposition hole into fractures intersecting the deposition holes. Q2 represents release from the deposition hole into the EDZ. Q3 represents release from the deposition hole to the tunnel and then into a fracture intersecting the tunnel. Since, according to the available data from Forsmark, there are so few fractures at repository depth, for many deposition holes there is no release through the path Q1. For each path, e.g. Q1, one particle is released.

5.3 Ramp and shaft variants

This study considers a number of variants where alternative properties are considered for the ramp and shafts. In some cases, the properties of the EDZ in the ramp and shafts are also varied. A summary of the cases are shown in Table 5-1. Additional realisations are performed for some cases. Commonly, the performance measures for specific deposition holes vary significantly between realisations, but the ensemble statistics are quite similar between realisations.

Figure 5-2 to Figure 5-7 present statistical results for the performance measures for some of the cases as normalised cumulative distribution function (CDF) plots for the performance measures for particles subjected to discharge. Figure 5-8 to Figure 5-13 present statistical results for the performance measures for some of the cases with particles subjected to recharge.The results show that changing the properties of the ramp and shafts or the EDZ for the ramp and shafts has little effect on the performance measure statistics or the distribution of performance measures. The differences in median or 10th percentile values between the cases are at most around 25% and usually much less.

Although there are differences in performance measures (particularly for t_r and U_r) between the different realisations considered for Alternative 2, there is little difference in performance measures between variants for a given realisation. This indicates that the effect of the ramp and shaft properties on performance measures is not sensitive to the realisation considered.

Discharge temperate conditions

The influence of the ramp and shaft properties on the performance measures for the discharge pathways to the repository is shown in the following plots. The discharge pathways are important for the transport of radionuclides to the surface.

Table 5-1. Variant case summary.

Case	Summary
Alternative 1A	Ramp and shafts filled with bentonite from the central area to –200 m, with coarsely crushed rock from –200 m to –50 m and with rock blocks (top sealing) above –50 m.
Alternative 1B	As for alternative 1A, but the shafts are filled with crushed compacted rock.
Alternative 2[1]	Ramp and shafts filled with bentonite from the central area to –370 m, with coarsely crushed rock from –370 m to –50 m and with rock blocks (top sealing) above –50 m.
Alternative 1A, more transmissive ramp/shaft EDZ	Alternative 1A, but with a hydraulic conductivity of $3.3\cdot10^{-6}$ m/s for the ramp and shaft EDZ.
Alternative 2, more transmissive ramp/shaft EDZ	Alternative 2, but with a hydraulic conductivity of $3.3\cdot10^{-6}$ m/s for the ramp and shaft EDZ.
Alternative 2, no ramp/shaft EDZ	Alternative 2, but with no ramp or shaft EDZ.

1) This variant is denoted Alternative 2A in the description above (Chapter 2). Alternative 2B is not modelled since, in comparison to Alternative 1A, Alternative 1B indicated that no significant difference results from that approach for the shafts.

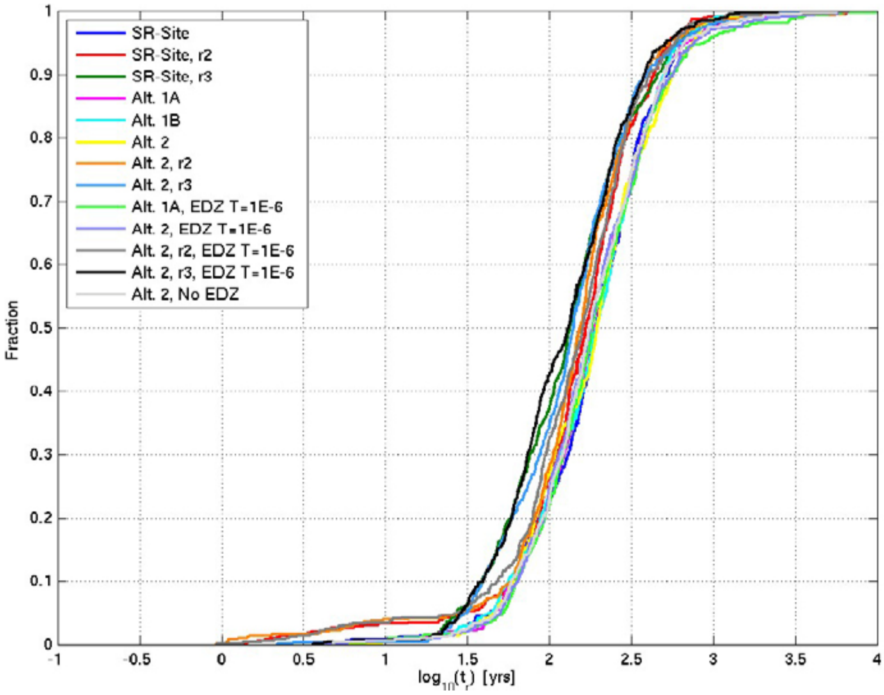


Figure 5-2. *Travel time in the rock, t_r; normalised CDF plots for Q1 discharge particles released at 2000 AD that successfully reach the model boundary (~25%).*

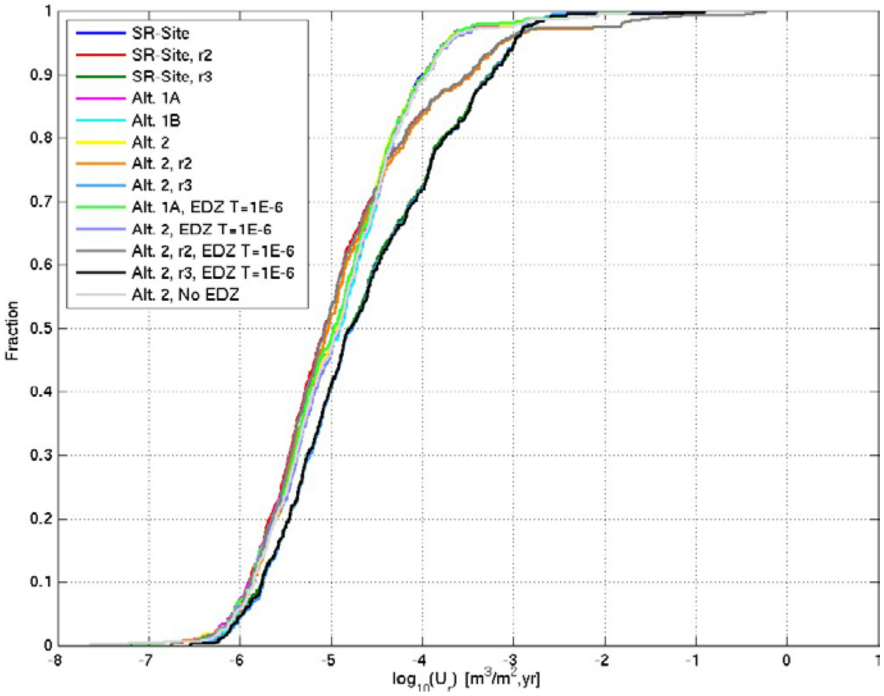


Figure 5-3. *Initial equivalent Darcy flux in the rock; U_r, normalised CDF plots for Q1 discharge particles released at 2000 AD that successfully reach the model boundary (~25%).*

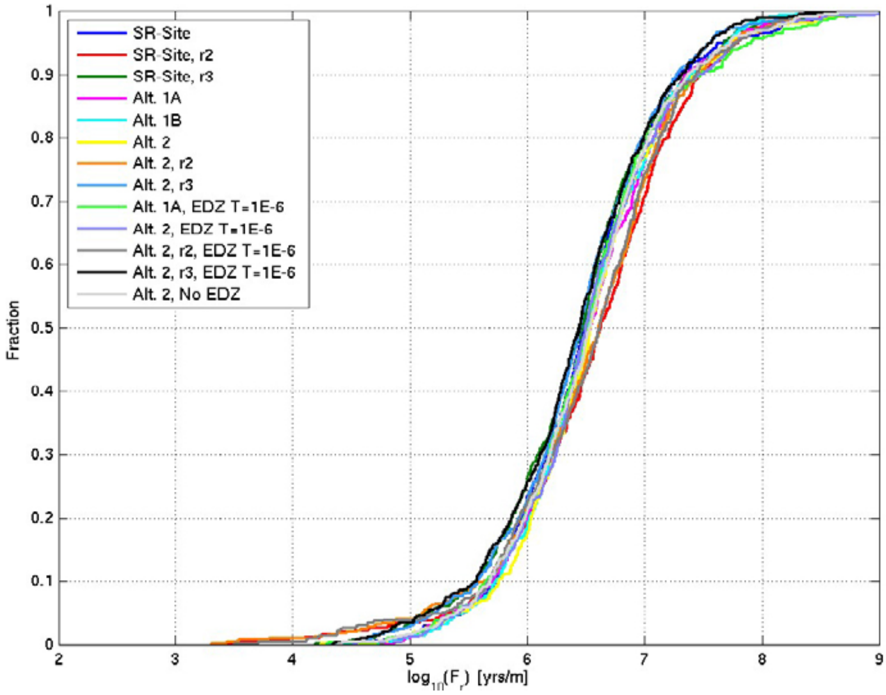


Figure 5-4. *Flow-related transport resistance in the rock; F_r, normalised CDF plots for Q1 discharge particles released at 2000 AD that successfully reach the model boundary (~25%).*

Discharge glacial conditions

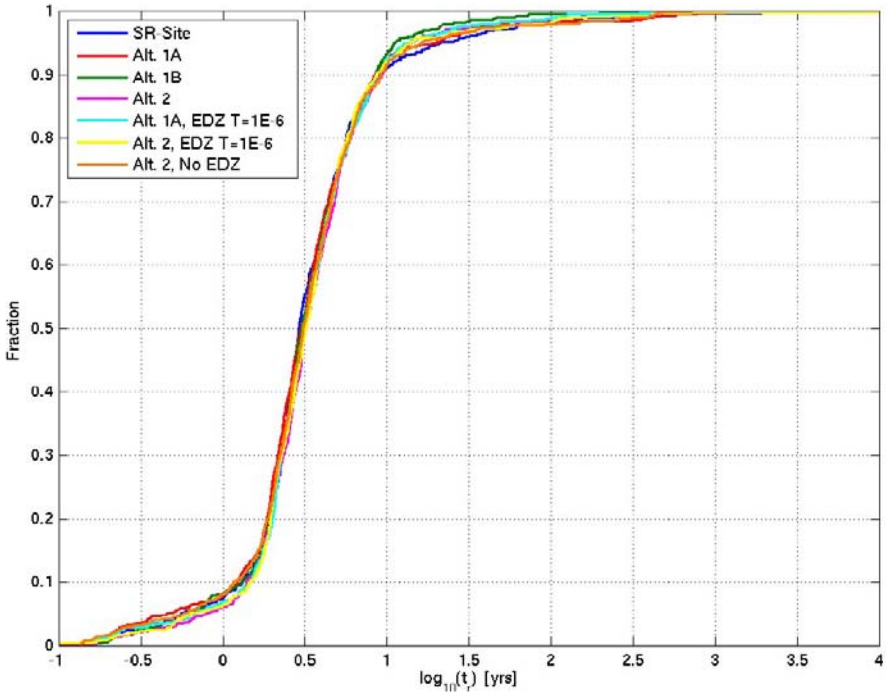


Figure 5-5. *Travel time in the rock, t_r; normalised CDF plots for Q1 discharge particles released for glacial ice front location II that successfully reach the model boundary (~29%).*

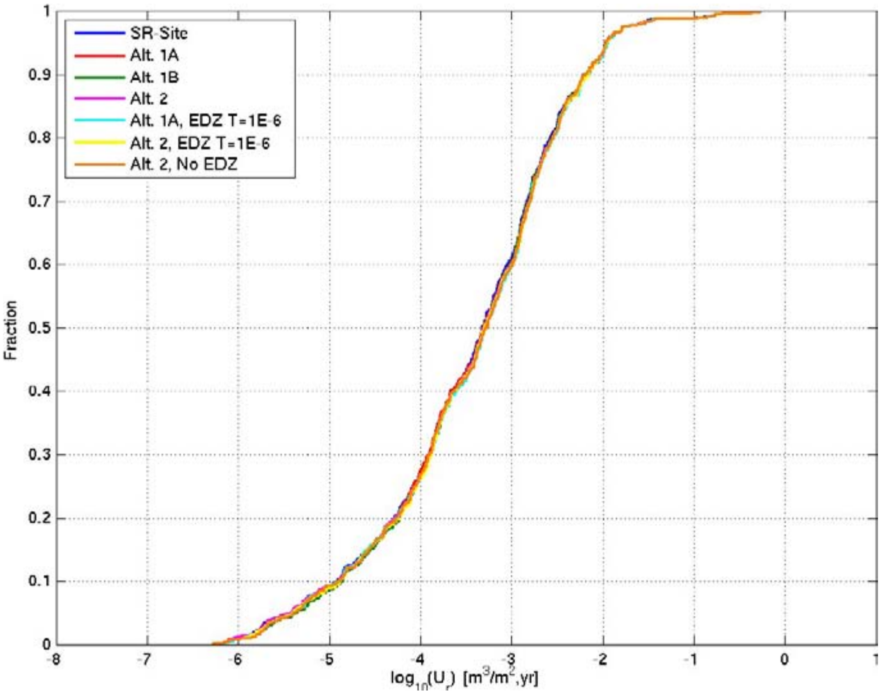


Figure 5-6. *Initial equivalent Darcy flux in the rock, U_r; normalised CDF plots for Q1 discharge particles released for glacial ice front location II that successfully reach the model boundary (~29%).*

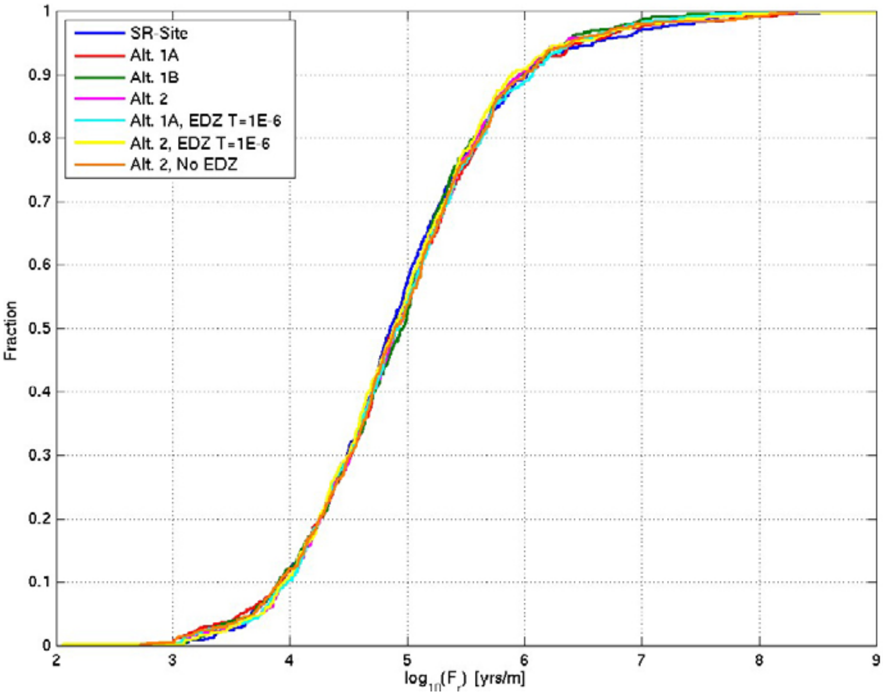


Figure 5-7. *Flow-related transport resistance in the rock, F_r; normalised CDF plots for Q1 discharge particles released for glacial ice front location II that successfully reach the model boundary (~29%).*

Recharge temperate conditions

The influence of the ramp and shaft properties on the performance measures for the recharge pathways to the repository is shown in the following figures. The recharge pathways are important for considering the flow of potentially dilute or oxygenated water to the repository.

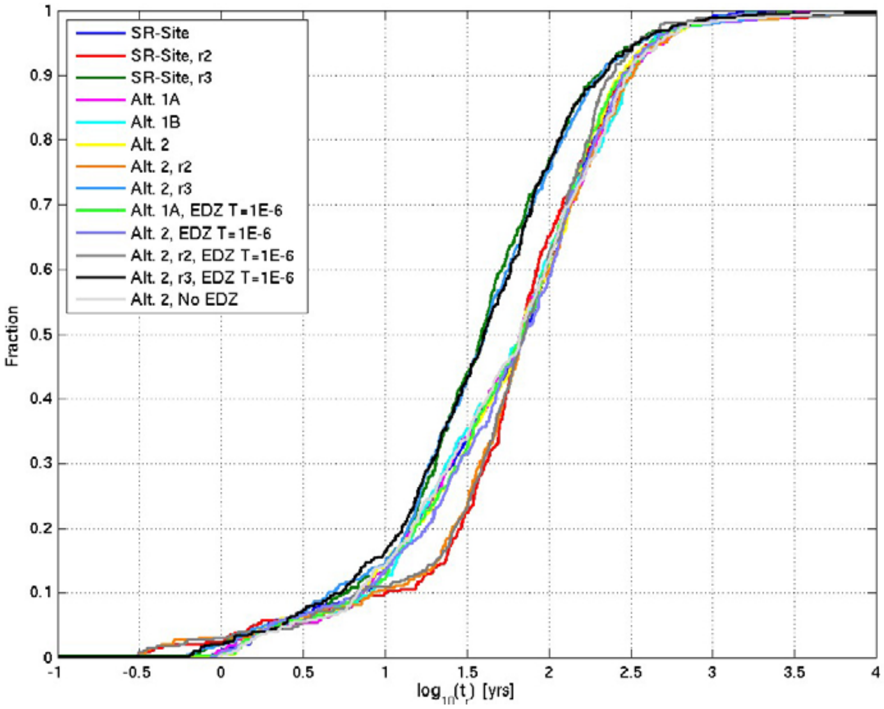


Figure 5-8. *Travel time in the rock, t_r; normalised CDF plots for Q1 recharge particles released at 2000 AD and successfully tracked back to the model boundary (16%–23%).*

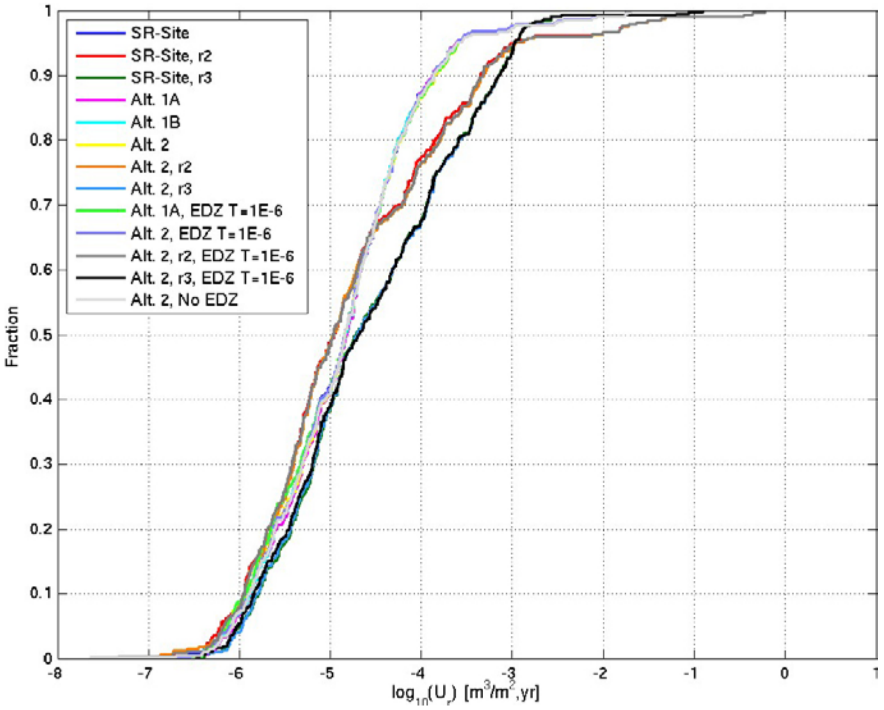


Figure 5-9. *Initial equivalent Darcy flux in the rock, U_r; normalised CDF plots for Q1 recharge particles released at 2000 AD and successfully tracked back to the model boundary (16%–23%).*

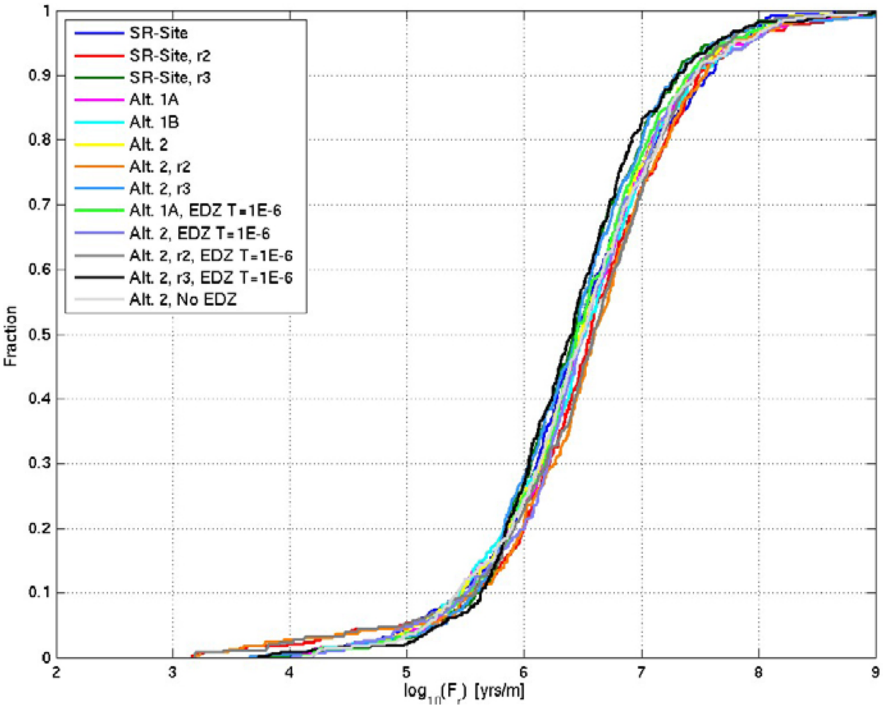


Figure 5-10. *Flow-related transport resistance in the rock, F_r; normalised CDF plots for Q1 recharge particles released at 2000 AD and successfully tracked back to the model boundary (16%–23%).*

Recharge glacial conditions

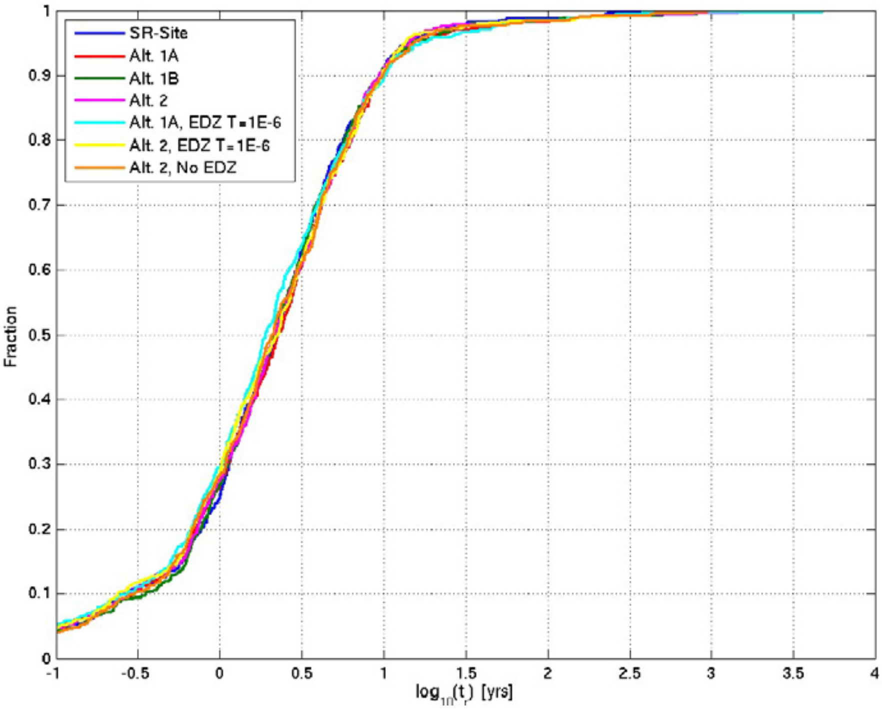


Figure 5-11. *Travel time in the rock, t_r; normalised CDF plots for Q1 recharge particles released for glacial ice front location II and successfully tracked back to the model boundary (~29%).*

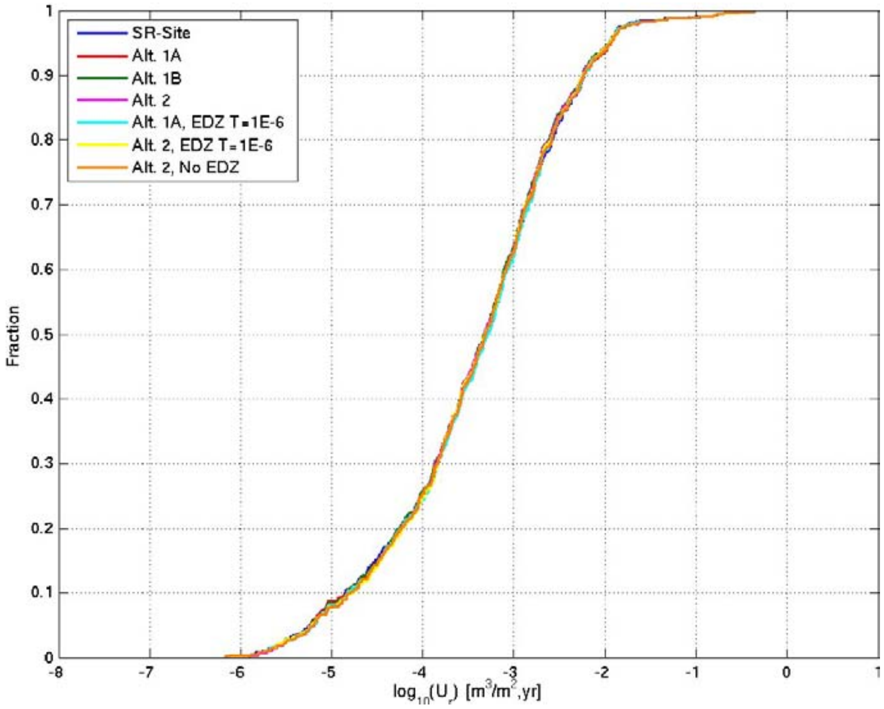


Figure 5-12. *Initial equivalent Darcy flux in the rock,* U_r*; normalised CDF plots for Q1 recharge particles released for glacial ice front location II and successfully tracked back to the model boundary (~29%).*

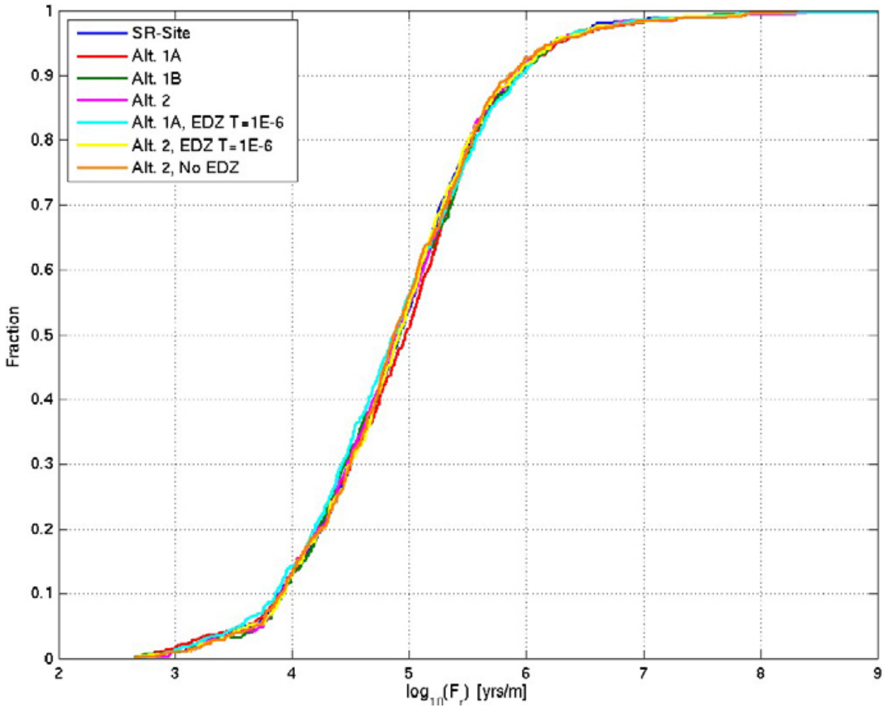


Figure 5-13. *Flow-related transport resistance in the rock,* F_r*; normalised CDF plots for Q1 recharge particles released for glacial ice front location II and successfully tracked back to the model boundary (~29%).*

Pathways

Figure 5-14 shows that for the Alternative 1A case at 2000 AD, the recharge pathways (purple) are mostly vertical and from below in the portion of the site covered by block 1. Even those few recharge pathways that originate on the top surface of the block 1 model are not close to the ramp. Therefore, the properties of the ramp and shafts have little effect on the performance measures of the recharge pathways in the model. The overall directions of the pathways are controlled by the regional model implementations that give the boundary conditions to the cases presented here.

Figure 5-14 also shows that the discharge pathways (orange) are mostly vertical and exit on the top surface of the block 1 model, i.e. the tops of the ramp and shafts are in a discharge area at 2000 AD. The exit points are dominated by the location of outcropping deformation zones, but a few particles exit near the ramp. This suggests that the properties of the ramp and shafts could have an effect on the performance measures for a few of the discharge pathways. This is reflected in minor changes to the t_r and F_r performance measures. The U_r performance measure is largely unaffected by the changes to the ramp and shaft properties since it is calculated at, or close to, the starting location. These locations are generally distant from the ramp and shafts and so is the flow at these locations, and hence U_r is unlikely to be significantly affected by their properties.

The Q2 and Q3 pathways seem to be less affected by changes in the ramp and shaft properties than the Q1 pathways. This suggests that the changes do not have a significant effect on the flows in the tunnels and EDZ. In the case of the EDZ, even though there is extensive connectivity between EDZ sections, the EDZ flow largely occurs between fractures intersecting tunnels, i.e. the flow is quite localised. Hence, changing the EDZ transmissivity in the ramp and shafts does not significantly affect the flow in the EDZ for the deposition tunnels.

Figure 5-15 shows a Q1 path for Alternative 2 at 2000 AD that uses a part of one of the shafts. However, there are only a few paths for each case that use the ramp or shafts. Also, only the upper parts of the ramp and shafts are used rather than the lower, bentonite-filled sections. For the glacial climate situation, the predominant flow towards the southeast carries particles away from the ramp and shafts, so they do not enter these structures.

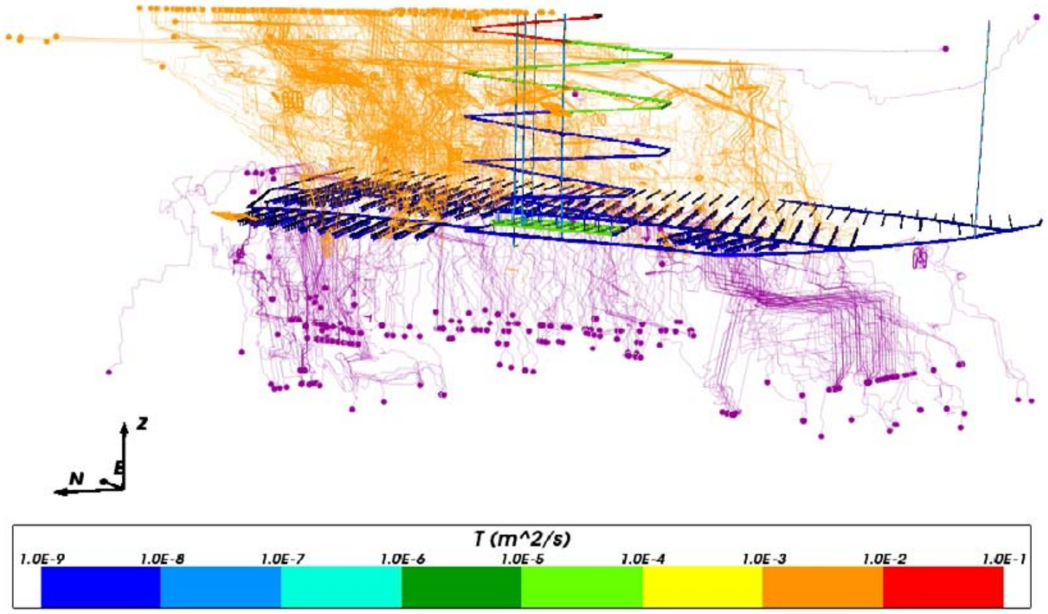


__Figure 5-14.__ Recharge (purple) and discharge (orange) pathways for the Q1 particles released at 2000 AD that successfully reach the model boundary (~24%) of the Alternative 1A case.

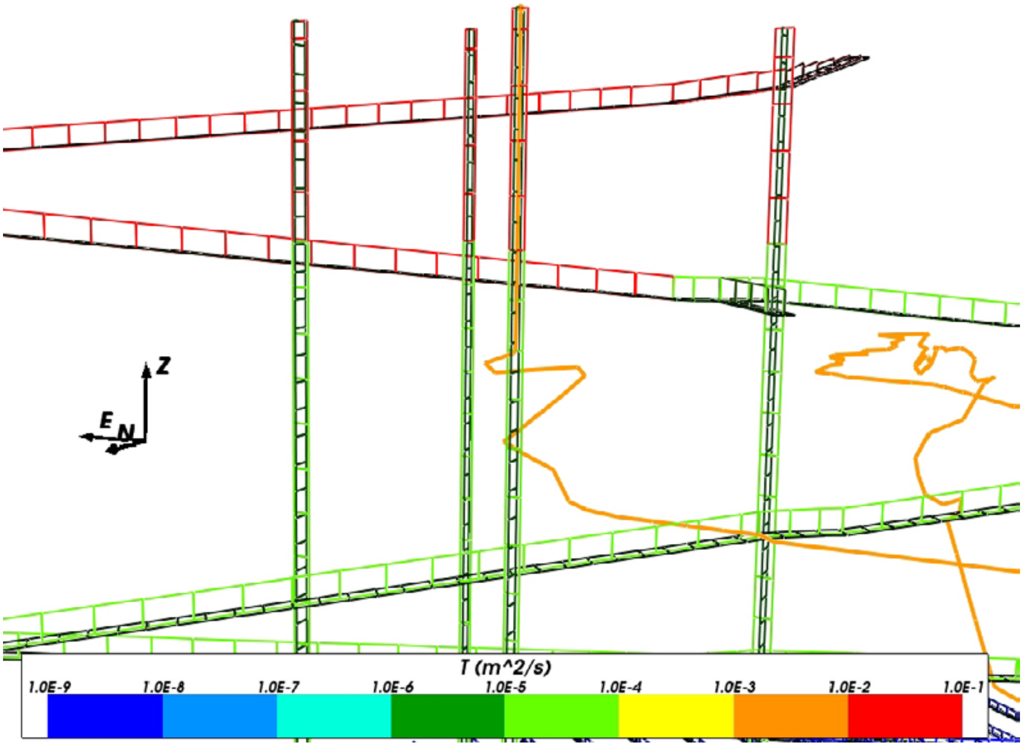


Figure 5-15. *Discharge pathway for a Q1 particle released at 2000 AD that travels along the upper part of a shaft in the Alternative 2 case.*

5.4 Sealing of investigation boreholes

A number of the modelled borehole cases were performed by varying the hydraulic properties of the boreholes for temperate (2000 AD) and glacial (ice front location II) climate conditions. For both conditions, particles are released in the paths Q1, Q2, and Q3. Three realisations are performed for temperate conditions. Some simplifications related to the representation of boreholes were made to the model. The main ones are:

- In the reference design, sections intersected by transmissive fracture zones are filled with silica concrete, which is permeable and erosion-resistant. In the model however, no such modification to the properties of the boreholes and surrounding fracture zones was done.
- In reality the boreholes have diameters that vary with depth, but in the model a uniform diameter was used. Also, all boreholes were assigned the same diameter even if the diameter varies between boreholes.
- In the model, the boreholes were assigned homogeneous properties (hydraulic conductivity and porosity), which is not necessarily the case in reality.
- A freshwater density was assigned to the boreholes, which should be a conservative assumption in terms of hydraulic driving forces. What the initial state in the boreholes should be after sealing is a matter of debate, however.

It is clear that there is no or little effect from the boreholes on the particle pathways when the borehole conductivity is less than 10^{-6} m/s. In order to have a significant impact on the pathways, at least in the sense of attracting particles, the borehole conductivity needs to be greater than 10^{-4} m/s. It is also clear that most of the particles enter cored (KFM) boreholes rather than percussion (HFM) boreholes. This could be explained by the fact that the HFM boreholes are shorter and therefore higher up in the rock. This makes them less likely to become a preferred pathway, since there are many other highly conductive structures encountered by the particles before they reach the HFM elevations. The results also show that a Q1 release location produces fewer particles that enter boreholes than Q2 and Q3. In general, fewer recharge particles enter the boreholes than discharge particles under temperate conditions, although only Q1 is analysed for recharge particles. Under glacial conditions the opposite situation prevails. Almost no discharge particles enter the boreholes under glacial conditions but quite a few recharge particles do. There are some differences in the number of particles entering boreholes between the different realisations. More than twice as many particles enter the boreholes in realisation 2 than in realisation 3 for one of the cases, indicating that there is some sensitivity to the realisation considered. However, since only two additional realisations were studied, it is difficult to draw any general conclusion about the variation between realisations.

The boreholes that attract most particles are KFM07B, KFM07C and KFM08C. The HFM boreholes and a few of the other KFM boreholes are also active to some extent in terms of attracting released particles, but not to the same degree. Under glacial conditions, KFM07B and KFM09B are the most frequently visited boreholes. The modelled boreholes can be seen in *Figure 5-16*.

Discharge temperate conditions

Statistical results for safety assessment performance measures are shown in *Figure 5-17* to *Figure 5-20*.

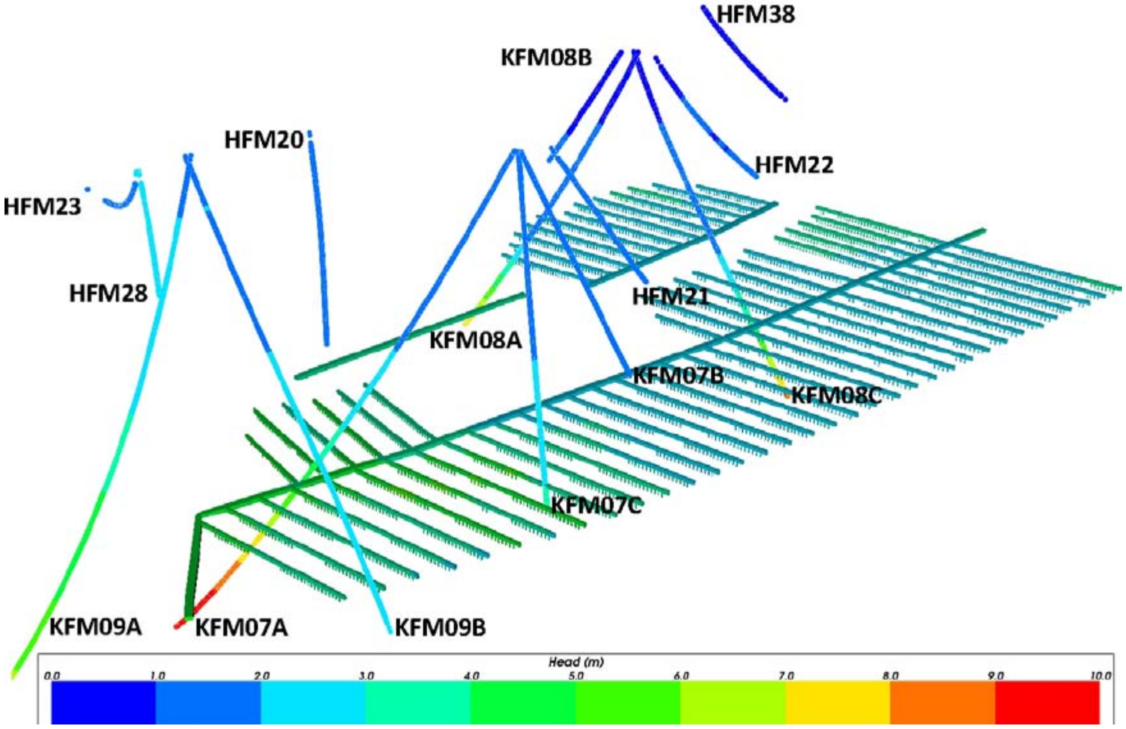


Figure 5-16. Modelled HFM and KFM boreholes shown together with the repository structures in block 1. All structures are coloured according to head (blue is low, red is high). The surrounding DFN model has been removed for visibility.

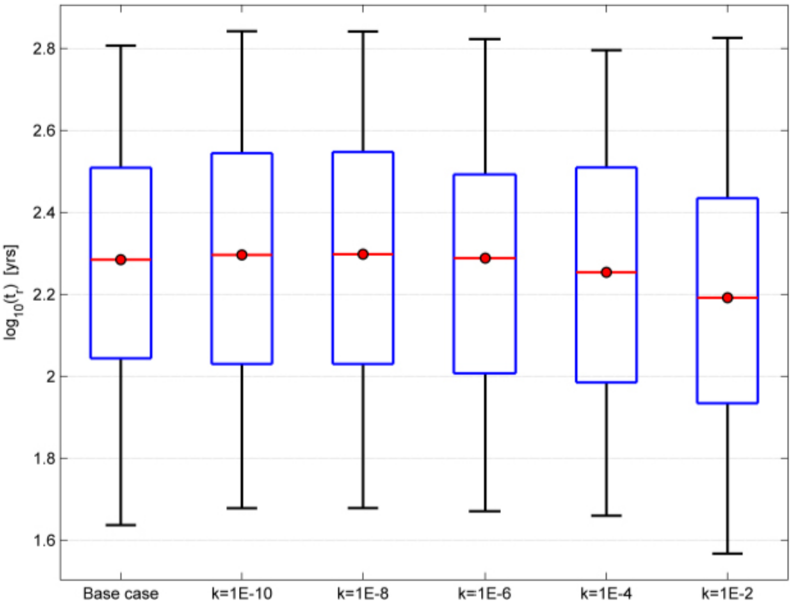


Figure 5-17. *Bar and whisker plot of t_r for the SR-Site Hydrogeological base case (Base case) and five different borehole sealing variants (conductivity in m/s) for all Q1 discharge particles released at 2000 AD that successfully reach the model boundary. The statistical measures are the median (red), 25th and 75th percentile (blue bar) and the 5th and 95th percentile (black "whiskers").*

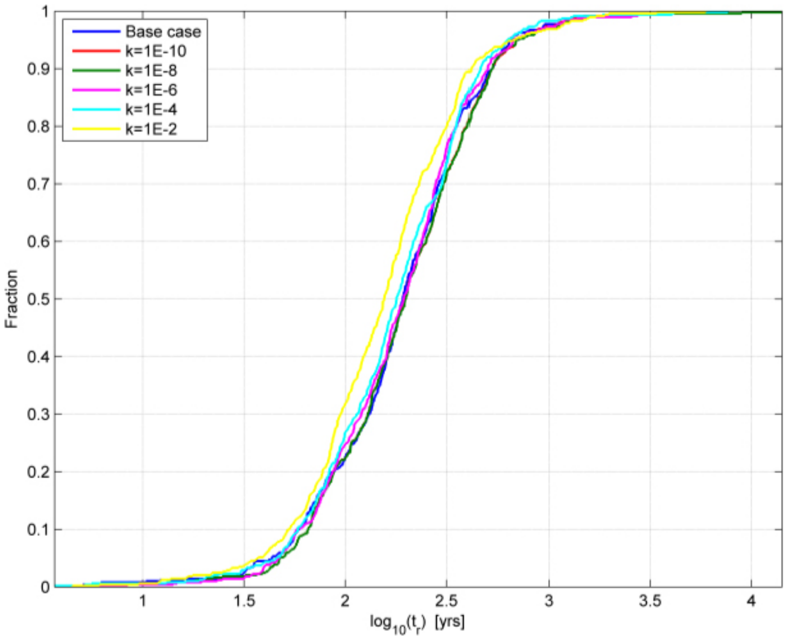


Figure 5-18. *Normalised CDF plot of t_r for the SR-Site Hydrogeological base case (Base case) and five different borehole sealing variants (conductivity in m/s) for all Q1 discharge particles released at 2000 AD that successfully reach the model boundary.*

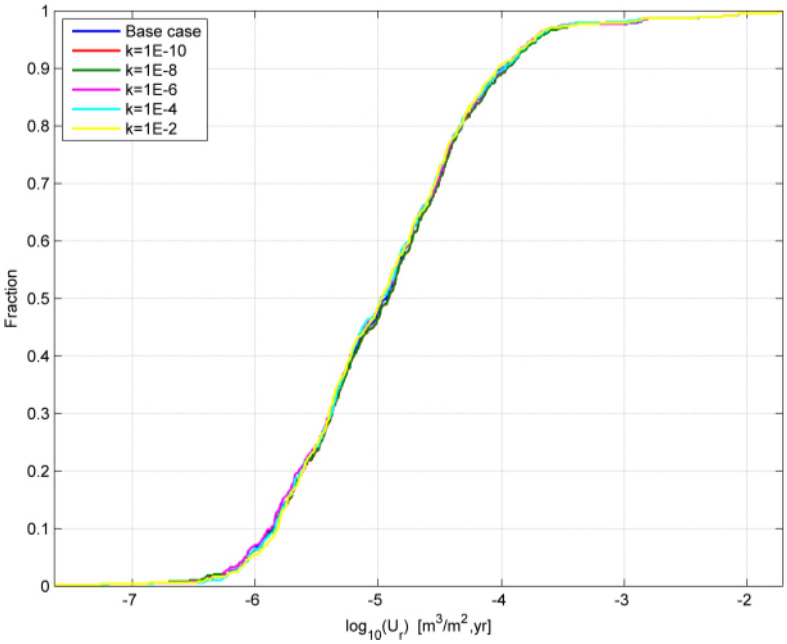


Figure 5-19. *Normalised CDF plot of U_r for the SR-Site Hydrogeological base case (Base case) and five different borehole sealing variants (conductivity in m/s) for all Q1 discharge particles released at 2000 AD that successfully reach the model boundary.*

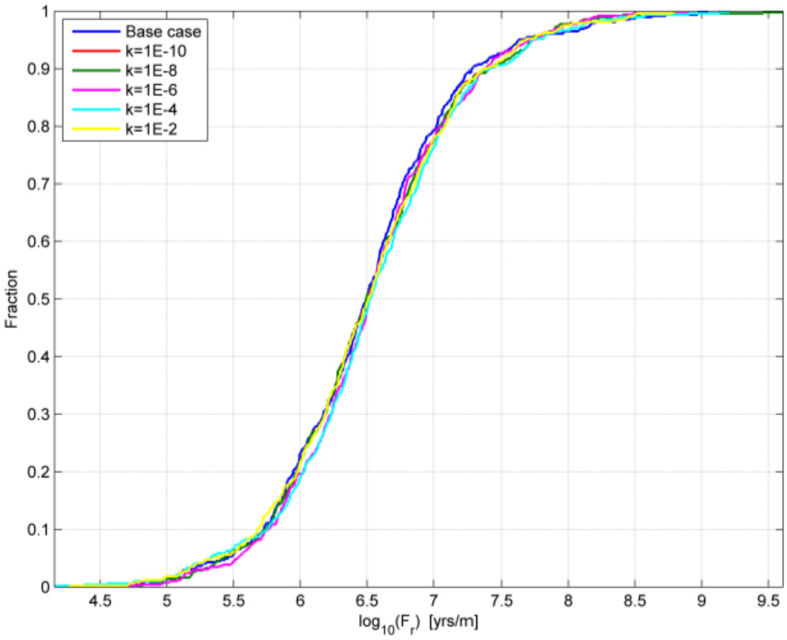


Figure 5-20. *Normalised CDF plot of F_r for the SR-Site Hydrogeological base case (Base case) and five different borehole sealing variants (conductivity in m/s) for all Q1 discharge particles released at 2000 AD that successfully reach the model boundary.*

5.5 Conclusions

Numerical simulations have been performed to investigate alternative properties for the design of the ramp, shafts, and investigation boreholes. In the simulations, two climate situations are considered: one during the temperate period soon after complete closure and re-saturation of the repository, and one during the glacial period when the ice front is located roughly above the middle of the repository (ice front location II) (Joyce et al. 2010). The temperate climate situation is believed to be quite plausible, and the situation with ice front location II is representing something of a worst case scenario. It is likely that the conclusions of this study will not change even if other climate scenarios are handled. This is valid for the ramp, the shafts, and the investigation boreholes.

5.5.1 Ramp and shaft variants

It can be concluded that within the context of the modelling reported here, the properties of the ramp and shafts and the properties of the EDZ for the ramp and shafts have little effect on the performance measure statistics or their distribution. The maximum difference in median values between cases is around 25% and most of the differences are much less for both the temperate and glacial climate situations. These differences are much less than those between several variants examined for SR-Site (Joyce et al. 2010), such as changing EDZ properties for all the tunnels, or even between different realisations of the HRD. A likely explanation for the small effects seen for this study is that the flows in the Forsmark models, and hence the particle pathways, are dominated by the deformation zones. The deformation zones tend to carry particles to the surface without involving the ramp or shafts.

However, there are effects seen for individual particle pathways when the ramp and shaft properties are changed. In some cases, exit locations are changed or particles use the ramp or shafts for part of their pathway.

Although there are differences in performance measures between the different realisations considered for alternative 2, there is little difference in performance measures between variants for a given realisation. This indicates that the effect of the ramp and shaft properties on performance measures is not sensitive to the realisation considered. It is of course possible that for other realisations, the performance measures may be more sensitive to the ramp and shaft properties.

The overall conclusion is that changing the ramp or shaft properties or the associated EDZ, within the scope reported here, has little effect on the overall recharge of potentially oxygenated or dilute water to the repository or on the discharge of radionuclides to the ground surface.

5.5.2 Sealing of investigation boreholes

The modelling of sealed boreholes conducted in the present report shows that the sealing properties of the boreholes have little effect on the performance measure statistics or their distribution. It has been shown that there is little or no effect from the boreholes on the particle pathways, recharge or discharge, when the borehole conductivity is less than 10^{-6} m/s. In order to have a significant impact on the pathways, at least in the sense of attracting particles, the borehole hydraulic conductivity needs to be greater than 10^{-4} m/s. The conclusion is the same for both of the modelled climate situations: the temperate and the glacial period. The differences between the variants in median and 10th percentile values stay within 28% and are usually much less when the ensemble results are compared. Even if the overall effect on the released particles is small, there are individual particles that show larger effects on the performance measure statistics. These are typically particles that enter the sealed boreholes. When only the subset of particles that enter the boreholes is analysed, an increased difference in performance measures can be seen when a given variant is compared for different realisations, but also when different variants within a given realisation are compared. Hence, some sensitivity to the choice of realisation can be seen in the results but the number of realisations analysed is too small to draw any general conclusion.

The small effect of the boreholes on the recharge and discharge pathways is likely due to low assigned conductivities, making the boreholes effectively invisible to flow in the bedrock. The recharge pathways indicate that no significant amount of potentially oxygenated water is drawn from the surface down to repository depths.

6 Important issues and continued technology development

6.1 Design premises

The current requirement on hydraulic conductivity is formulated as follows:

> *The closure in boreholes, shafts and tunnels that are not deposition tunnels shall prevent conductive channels that could jeopardise the rock's barrier function from forming between the repository and the surface (Requirement SSCL18, see Appendix A, Table A-1). Below the location of the top seal, the integrated effective connected hydraulic conductivity of the backfill in tunnels, ramp and shafts and the EDZ surrounding them must be less than 10^{-8} m/s. This value need not be upheld in sections where e.g. the tunnel or ramp passes highly transmissive zones (Requirement SRCAN178, see Appendix A, Table A-2).*

An analysis and assessment of how different closure alternatives impact the water flow in the repository is presented in Chapter 5. The conclusion is that the difference in flow is only marginal if the level for competent sealing is lowered from about 250 m to 100 m above the repository level.

In view of this there is reason to consider changing the formulation of the requirement:

The backfilled tunnels must not adversely impact the water flow through the repository. Groundwater flow modelling shows that this requirement is met if the ramp and shafts are backfilled with a material that has a hydraulic conductivity $< 10^{-8}$ m/s up to 100 m above repository level. In the case of tunnel sections that are backfilled with such a material, the EDZ must have the same hydraulic conductivity or lower.

It is possible that the level for competent sealing can be further lowered; this can be studied in the further optimisation of the repository and its closure. As far as the requirement on the hydraulic conductivity of the backfill material in the ramp is concerned, a certain swelling pressure is needed to guarantee good contact with the roof and that any channels or small unfilled pockets from the installation work are sealed by the swelling bentonite. If this requirement is met, the hydraulic conductivity will be lower than 10^{-8} m/s. In other words, in the case of the ramp there is no reason to study whether backfill with a higher conductivity would meet the general requirements. But in the case of the shafts, it would facilitate installation if the hydraulic conductivity requirement could be relaxed. This should be studied in conjunction with optimisation of the closure of the repository.

6.2 Sealing of the ramp with swelling clay

6.2.1 Detailed design

This type of closure is based on the reference design for backfilling of deposition tunnels that is described in the application. The difference compared to the deposition tunnels is that the dimensions are different and the requirements on the fill materials are laxer. There is no requirement on low compressibility, and the requirement on hydraulic conductivity is lower.

The less stringent requirements allow the possibility of filling the tunnels only with pellets of swelling clay or blocks and pellets with a lower swelling mineral content. These variants should also be compared in terms of cost-effectiveness and robustness. It is possible that the variant where only pellets are used can handle more inflowing water, see next section. If the ramp is filled with blocks and pellets, the method and technology that is developed for the deposition tunnels can be adapted to the geometry and the requirements that apply to the ramp. If the ramp is to be filled only with pellets or granules, studies and development of the installation method are required. It needs to be determined whether sufficiently high density can be achieved when the ramp is backfilled under production conditions. To achieve sufficiently high density, the granules must be of high density and the granule size distribution has to be adjusted so that the macropore content is low. Furthermore, a study is needed to determine how such backfill works for expected water inflows to the ramp.

It should also be determined whether a sufficiently high installation pace can be maintained in backfilling under production conditions to avoid problems with water. If the macropore content is low, the density increases at the same time as the granule/pellet fill is presumably able to absorb and store a smaller volume of water. This may have to be adjusted so that an optimal balance of high density and good water storage capacity are achieved.

Regardless of which sealing alternative is chosen, a description of material requirements, density and proportions of blocks and pellets is needed as a basis for the long-term safety assessment. A description of how installation is to be carried out and inspected is also needed.

6.2.2 Water handling

The detailed design of the closure will be adapted according to the amount and distribution of inflowing water. This mainly applies to ramp, shafts, and main and transport tunnels. Since the central area is planned to be backfilled with crushed rock, inflowing water is not expected to pose any major practical problems.

In principle, the same processes are to be taken into consideration for shafts, ramp, and main and transport tunnels. This is described below for the ramp.

The water inflow to the backfilled part of the ramp will, if it is sufficiently high, create channels in the fill material (piping). These channels may be permanent so that the requirements on low hydraulic conductivity are not met. Water seepage from the tunnel roof and walls could cause water to collect on the top surface of the fill, which would hinder the installation work since the bentonite could begin to swell.

The standard method:

The standard method for handling the inflowing water is to fill the ramp so rapidly that as long a section as possible can be filled before seeping water has created water-conducting channels all the way up to the fill face. When this happens, a mechanical and hydraulic plug is installed according to the same principle as is used for the deposition tunnels. When this plug is in place, filling of the ramp can continue until the fill cannot store more water and a new plug is installed. The placement of the plugs is planned in advance based on knowledge of how much water the fill material can store and how much water runs into the different parts of the ramp. The method is the same regardless of whether the ramp is filled with blocks and pellets or only pellets. If only pellets are used, the macropore content is greater and a larger quantity of water can potentially be stored before a plug has to be installed. The disadvantage of pellets is that it is not possible to achieve as high density, which means that a higher-quality material has to be used in order to satisfy the requirements.

The water that flows into the ramp above the fill face is handled by installation of dams/weirs. The spacing between the weirs is determined by the inflow and the requirement that the water must be able to be pumped away before it reaches the fill face. These weirs can be installed just before closure do not have to be planned when the ramp is built.

The spacing between the plugs can be increased by designing the fill material so that it can absorb and hold as much water as possible. The optimal fill material absorbs water until all macropores, i.e. pores between pellets and blocks, are filled with water, after which it releases the water in a controlled manner.

Optimised standard method

The backfill is divided up by layers with high flow resistance. This ensures that a high proportion of the available pore volume is filled with water before a channel to the backfill face is formed. This can be accomplished in different ways. The layer with high flow resistance could consist of pellets that have been given a higher water ratio at installation. Another alternative is to install a layer of shotcrete. The purpose of this layer is not to create a mechanical restraint, but merely to make sure that a large proportion of the available pore volume is used to store water. It is important to understand how trapped air interacts with the inflowing water so that gas pressure cannot be built up.

Handling of large water flows

Where the ramp passes a zone with high inflow, plugs are placed on both sides of the water-bearing zone and the section between the plugs is filled with crushed rock.

How inflowing water interacts with backfill consisting of bentonite blocks and pellets has been studied in SKB's project for backfilling of the deposition tunnels, see e.g. Dixon et al. (2011). Further studies on handling of water inflow is ongoing as a part of SKB:s technology development for backfilling of deposition tunnels.

6.3 Sealing of shafts with swelling clay

Handling of water and bentonite is a challenge in connection with sealing of shafts with swelling clay. The working environment in connection with work in shafts is also important to consider.

In the same way as for the ramp, the problem with water involves firstly inflow to the parts of the shaft where the bentonite fill has been installed, and secondly handling the water inflow coming from above from the unfilled part of the shaft. Proven methods and equipment are available for handling of water during work in shafts. The water inflow to the backfilled part of a shaft can, if it is great enough, create channels in the fill material (piping). These channels may be permanent so that the requirements on low hydraulic conductivity are not met. The water coming from above can collect on the top surface, which hinders the installation work since the bentonite can then begin to swell.

Two installation methods are being considered: installing bentonite blocks and pellets in the same way as is planned for deposition tunnels, and installing a specially developed pellet mixture.

The former method is judged to be difficult to use in a vertical shaft with inflowing water.
The second method may be feasible, but some research and development work remains to be done to demonstrate this. The size of the water inflow in the shafts is what will determine whether the method is possible or not. The first step in showing that the method is feasible is to compile relevant knowledge obtained by SKB, mainly in projects for development of backfilling of deposition tunnels. Subsequently, it needs to be determined whether sufficiently high density can be achieved in backfilling of the shaft under production conditions. To achieve sufficiently high density, the granules must be of high density and the granule size distribution has to be adjusted so that the macropore content is low. Furthermore, a study is needed to determine how such backfill works in the face of expected water inflows. It should also be determined whether a sufficiently high installation pace can be maintained in backfilling under production conditions to avoid problems with water. If the content of macropores, which can contribute to the rapid absorption of water, is low, the density increases at the same time as the granule/pellet fill is presumably able to absorb and store a smaller volume of water. This may have to be adjusted so that an optimal balance of high density and good water storage capacity are achieved. This knowledge then needs to be supplemented by practical tests of shaft backfilling on a small scale. The pellets, installation method etc can be designed based on the results that are obtained. The permitted water inflow for installation to be practically feasible is based on the results of tests and existing knowledge. A prerequisite for practical feasibility is that installation can be done rapidly and that the installation can be inspected.

Another potentially interesting installation method that should be evaluated is dumping material down into the shaft.

6.4 Filling of shafts with crushed rock

This alternative has advantages, since the crushed rock potentially is less sensitive to water inflow. However, the alternative has only been evaluated in the desk study presented in this report. Further, studies are needed to verify the judgement that this method is less sensitive to water inflow and that the crushed rock provides sufficiently low hydraulic conductivity.

Methods for installation and quality control in shafts have to be developed. Furthermore, the impact of the water inflow to the shafts on the installation procedure needs to be studied for this alternative as well. However, it is expected to be a less challenging task than in the case of bentonite-filled shafts. The risk of piping and erosion in the installed fill needs to be studied, however. An efficient installation method, such as dumping material down the shaft, which is often used for backfilling of mines, should be able to be adapted to this application. Such a procedure permits rapid installation, which is good from a cost point of view. However, it is important that the installation method not lead to separation, which has a detrimental effect on the density of the material. Not needing to have personnel in the shaft who manually install and inspect the backfill is an advantage from an occupational safety viewpoint. Another question that needs to be studied is whether it is possible to carry out quality control in an adequate manner. In laboratory tests where low conductivity has been measured on crushed rock, the material has been installed and carefully compacted in a lab setting. It remains to be shown whether it is possible to install and compact the material sufficiently rapidly and well under actual conditions.

Further, it needs to be determined how a well balanced grain size distribution curve can be achieved in large-scale production. In preparatory tests for the Prototype Repository, it was found that a sufficiently good grain size distribution curve could not be obtained by merely crushing the rock. The conclusion was that some of the crushed rock also needs to be ground in order to obtain enough fine material, see Gunnarsson et al. (2001).

6.5 Top seal and central area

Detailed designs for both top sealing and backfilling of the central area need to be developed. Requirements and other design premises need to be gone through and updated, if necessary.

6.6 Main tunnels and transport tunnels

When higher-resolution predictions for water inflow to main and transport tunnels are available, a detailed plan, including work sequence, needs to be prepared for sealing of these tunnels. At high water inflows, plugs may be needed to handle the water during sealing. If plugs should be needed in the main tunnels, this may affect the layout. Plugs for separating the bentonite-filled parts of the repository from the central area need to be developed. In order to determine whether sealing issues exist that can affect the layout, the work sequence for sealing needs to be described.

6.7 Crushed rock in ramp

The requirements that are made on the actual fill in this alternative are not difficult to satisfy. Nor is the installation technology complicated. When only crushed rock is used, however, a gap at the roof cannot be avoided. If this gap is to be avoided, some type of swelling material must be used. A survey of suitable materials then has to be done. An important factor is how long the fill must be in contact with the roof, and how it can be shown that this has been achieved. If a swelling clay is to be used, the crushed rock fill needs to be given a grain size distribution that reduces erosion of the swelling clay to the available pore volume in the crushed rock. One possible design is to install a filter material between the crushed rock and the bentonite clay at the roof. However, this would presumably make the installation procedure unacceptably complicated. There is also a need to evaluate filter materials between the fill of crushed rock and the parts of the ramp that are completely filled with swelling clay. A separating plug of the type (earth dam plug) that has been studied for the closure of SFR (Luterkort and Bertilsson 2011) could, for example, be used.

6.8 Borehole sealing

The alternative of backfilling the whole borehole with crushed rock needs to be further studied. Of particular interest is whether it is practically possible to install crushed rock with a suitable grain size distribution curve with sufficiently high density without the material separating. As a first step in this development work, this can be tested in the field in short borehole sections where it is possible to measure the resulting density for different installation methods and evaluate the sensitivity of the method to circumstances during installation.

As a second step, installation in full-length boreholes should be investigated and tested.

Regarding the alternative of using different types of concrete, the plan for technology development is similar to that for crushed rock, but considerably more experience is available from conventional rock construction.

As far as the reference design is concerned, technology development is mainly needed regarding:

- Improved quality control, e.g. inspection to ensure that installed components such as quartz plugs end up in the right place.
- Stabilization of boreholes prior to sealing.
- Full-scale tests to verify the method.

6.9 Plugs

In order to be able to install the various sealing components, installation plugs will be needed. The most important function of the plugs will be to permit installation of the swelling clay sections by hydraulically closing off various openings. The plugs will also separate different closure materials from each other. A number of different plugs with varying geometry will be needed. A survey of tunnel plugs for different applications has been done and the results reported in Dixon et al. (2009). The plugs are assumed to have the same basic design as the plugs for the deposition tunnels. Further studies are needed to determine how the plugs should be designed to meet the stipulated requirements. Similar studies are being done today in the project for extension of SFR (Luterkort and Bertilsson 2012). See also SKBdoc 1334119. Another type of shaft seal is currently being tested in Canada (Martino et al. 2011, Holowick et al. 2011).

The questions surrounding the long-term performance of the concrete plugs also make it necessary to study what happens when the concrete has degraded to the point where the bentonite is no longer held in place.

6.10 Rock support

The extent to which rock support materials, mainly shotcrete, should be removed before sealing is carried out needs to be investigated. In order to ensure the required watertightness of the closure, the remaining rock support may not form contiguous volumes that short-circuit those parts of shafts and ramp that are filled with bentonite. How this can be done without an unacceptable risk of workplace accidents needs to be studied.

6.11 Long-term durability

An issue that is not discussed in the report – but that will need to be evaluated – is the long-term durability of different closure alternatives. This includes, for example, the impact of permafrost and glacial meltwaters.

7 Recommendations

The analyses and assessments that have been performed within the project show that the reference design can be simplified and that sealing can be done more cost-effective without compromising safety. The following *reference design* is proposed for sealing of ramp and shafts:

> The ramp is filled with swelling clay in the form of blocks and pellets or only pellets from the repository level and 100 m upward. Between 100 m above the repository level and 50 m below ground level, the ramp is filled with crushed rock. The uppermost part of the ramp is filled with stone blocks of varying size. The fill is then injected with concrete grout. The shafts are filled with crushed rock that has been optimised for low hydraulic conductivity, from repository level all the way up to the top seal.

This concept is judged to meet the requirements on long-term safety. At the same time, the concept is judged to be the most cost-effective solution and the alternative that requires the least transport and thereby has the least environmental impact.

Installing crushed rock instead of swelling clay in the shafts is also judged to be more robust and entail lower risks in production and installation of the seal. This needs to be verified by further studies and tests, however.

In order to fulfill the requirement on "proven or tested" technology further technology development and demonstration for sealing of shafts is needed. As far as the ramp is concerned, it is easier to argue that the technology is already tested and refer to the tests of backfilling of deposition tunnels that will be carried out in 2012. The recommendation is to continue to develop the technology of backfilling the ramp and perhaps main and transport tunnels with pellets. This is deemed to have a potential for handling more water and thereby for reducing the number of plugs that are needed in the ramp (and in main and transport tunnels). This would make the solution more cost-effective and robust.

Further, the results of analyses and evaluations show that the design premises with respect to long-term safety for sealing of investigation holes can be relaxed. The following is proposed as a new *design premise*:

> The resulting hydraulic conductivity over the length of the borehole shall be lower than 10^{-6} m/s.

Analysis results do not support proposing a new reference design for sealing of investigation boreholes. The most important reason is that the simpler alternatives that could satisfy the new requirements, for example sealing the investigation boreholes with crushed rock that has been optimised for low hydraulic conductivity or plugging the holes with concrete, are not as technologically mature as the current reference design. Further studies are needed before it is possible to change the reference design, including tests and trials of alternative designs.

References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.se/publications.

References to SKB's unpublished documents are listed separately at the end of the reference list.

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Unpublished documents

SKBdoc id, version	Title	Issuer, year
1334119 ver 1.0	Konceptuell utformning av pluggar för förslutning av SFR	Vattenfall Research and Development, 2012

Appendix A

Requirements and design premises

Table A-1. Requirements level 3 and 4.

ID	Requirements level 3: Subsystem requirements for closure*	Requirements level 4: Design requirements closure*
Nuclear safety and radiation protection		
SSCL18	**Restrict water flow** The closure in boreholes, shafts and tunnels that are not deposition tunnels shall prevent conductive channels that could jeopardise the rock's barrier function from forming between the repository and the surface.	In passages through hydraulic rock domains (HDRs) at depths where freezing is limited, the closure material in boreholes, shafts and tunnels shall, at the installed density, prevent advective transport (Requirement DRCL21). In order to prevent the formation of conductive channels between the repository and the ground surface, closure that limits advective transport shall be mechanically and hydraulically separated from other closure (Requirement DRCL22).
SSCL43	**Keep the closure in deposition tunnels in place** The closure in main tunnels shall prevent the backfill from swelling/expanding or being transported out of the deposition tunnels.	The closure material in the main tunnel shall, at the installed density, provide sufficient restraint to limit the swelling/expansion of the backfill so that the backfill's barrier functions are not significantly degraded (Requirement DRCL23).
SSCL49	**Keep the closure in adjoining openings in place** The closure shall keep the closure in adjoining or underlying underground openings in place.	Closure material used in the central area's rock caverns and in top seals shall remain in place in the final repository and not diminish significantly in volume (Requirement DRCL24).
SSCL26	**Significantly obstruct inadvertent intrusion in the final repository** The closure in the uppermost parts of ramp, shafts and boreholes shall significantly obstruct inadvertent intrusion in the final repository.	The mechanical properties of the top seal shall be such that excavating or digging out the seal with currently know methods entails considerable effort (Requirement DRCL25).
SSCL42	**Long-term durable** The closure shall be long-term durable and maintain its barrier functions in the environment expected in the final repository.	The composition and density of the installed closure material shall be such that its functions are upheld and retained for a long time (Requirement DRCL26).
SSCL20	**Not impair the barrier functions of the barriers** The closure must not significantly impair the barrier functions of the other barriers.	The mechanical properties of the closure in the underground openings in the central area shall be such that it prevents significant convergence of surrounding rock walls and consolidation in the surrounding rock (Requirement DRCL27). The closure material may not contain substances that can significantly degrade the barrier functions of the rock or the engineered barriers (Requirement DRCL35).
SSCL22	**Based on proven technology** The closure and methods for manufacturing, installation, test and inspection shall be based on well-tried or tested technology.	
SSCL23	**Reliably produced** Closure with specified properties shall be possible to manufacture and install with high reliability.	
SSCL24	**Verifiable** The properties of the closure shall be possible to inspect against specified acceptance criteria.	
SSCL25	**Contribute to good protective capability and sustainability** The closure shall contribute towards ensuring that the protective capacity of the final repository will be as good as can reasonably be achieved.	

ID	Requirements level 3: Subsystem requirements for closure*	Requirements level 4: Design requirements closure*
Environmental impact		
SSCL37	**Discharge into water** In the design of methods for the preparation and installation of closure, consideration shall be given to discharges into water.	
SSCL38	**Noise and vibration** In the design of methods for the preparation and installation of closure, consideration shall be given to noise and vibrations.	
SSCL39	**Emissions into the air** In the design of methods for the preparation and installation of closure, consideration shall be given to emissions into the air.	
SSCL40	**Economizing with energy and resources Consideration** shall be given in the choice of closure materials and the installation of closure to economizing with energy and resources.	
SSCL41	**Environmentally-oriented product choice** Materials and consumables with a limited impact on the environment shall be chosen for use in the preparation and installation of the closure.	
Other occupational safety and health considerations		
SSCL32	**Small health and accident risks** Methods for preparation and installation of the closure must not involve unacceptable risks of health effects and accidents for people in or around the facility..	
Quality, flexibility and cost-effectiveness		
SSCL34	**Cost-effective** The closure and methods for manufacturing or preparation, inspection and installation shall be cost-effective.	

* The official requirements are written in Swedish, the presented translations are unofficial.

Table A-2. Requirements level 4 and Design premises, long-term safety.

ID	Requirements level 4: Design requirements, closure*	Linked design premise from “Design premises, long-term safety”
Definitions and background		
Closure		
DRCL14	The closure is one of the engineered barriers in the KBS-3 repository.	
DRCL15	The closure is the material that is installed in boreholes and underground openings other than deposition tunnels and in order to fill and close them.	
Initial state		
DRCL17	The initial state of the closure is the state when all closure material in a specific borehole or underground opening is installed and the borehole, rock cavity, shaft or tunnel has been closed. Inflow of groundwater to an underground opening or a borehole and its impact on the closure is not included in the initial state.	
Scope		
DRCL18	The design premises presented in this document include design requirements on and premises for: • Choice and specification of material. • The density and geometric configuration of the installed closure. • Methods for preparation of materials and manufacturing of pellets and blocks. • Methods for handling and storage of materials, pellets and blocks. • Methods for installation in the different underground openings and boreholes. • Methods for test and inspection of materials, installation and installed closure.	
DRCL19	This document state the design requirements for the closure for it to sustain the functions and properties stated in the subsystem requirements. The design requirementsconstitute together with the design premises related (linked) to them, basis for the design of closure material and components, installed closure, methods for manufacturing, installation and inspection. The design requirements state conditions every specific design must fulfil. The linked design premises state the premises given which the design requirements shall be fulfilled.	
Basic design		
DRCL20	Closure in investigation boreholes and underground openings where the flow of water shall be restricted consists of pre-compacted bentonite clay components that are installed in the investigation boreholes or underground openings.	
DRCL36	Closure in underground openings where there are no restrictions on flow of water consists of rock material that has been compacted in situ in the underground opening.	
DRCL37	Closure in the upper part of underground openings that connect to the surface consists of tightly fitted rock blocks to prevent intrusion.	
Design of the closure		

ID	Requirements level 4: Design requirements, closure*	Linked design premise from "Design premises, long-term safety"
Requirements related to the barrier functions in the KBS-3 repository		
DRCL21	In passages through hydraulic rock domains (HDRs) with limited risk of freezing, the closure material in boreholes, shafts and tunnels shall, at the installed density, limit advective transport.	Below the location of the top seal, the integrated effective connected hydraulic conductivity of the backfill in tunnels, ramp and shafts and the EDZ surrounding them must be less than 10^{-8} m/s. This value need not be upheld in sections where e.g. the tunnel or ramp passes highly transmissive zones *(*Requirement SRCAN178)*.* The depth of the top seal can be adapted to the expected depth of permafrost during the assessment period, but must not be deeper than 100 m above repository depth (Requirement SRCAN179). Boreholes must be sealed such that they do not unduly impair the containment or retention properties of the repository. This is preliminarily achieved if the hydraulic conductivity of the borehole seal < 10^{-8}m/s, which is ensured if the swelling pressure of the seal is > 0.1 MPa. This value need not be upheld in sections where e.g. hole passes highly transmissive zones *(*SRCAN191). The top seal has no requirements on hydraulic conductivity (Requirement SRCAN210).
DRCL22	In order to prevent the formation of conductive channels between the repository and the surface, closure that limits advective transport shall be mechanically and hydraulically separated from other closure.	Below the location of the top seal, the integrated effective connected hydraulic conductivity of the backfill in tunnels, ramp and shafts and the EDZ surrounding them must be less than 10^{-8} m/s. This value need not be upheld in sections where e.g. the tunnel or ramp passes highly transmissive zones (Requirement SRCAN178). Boreholes must be sealed such that they do not unduly impair the containment or retention properties of the repository. This is preliminarily achieved if the hydraulic conductivity of the borehole seal < 10^{-8}m/s, which is ensured if the swelling pressure of the seal is > 0.1 MPa. This value need not be upheld in sections where e.g. hole passes highly transmissive zones (Requirement SRCAN191).
DRCL34	In order to prevent the formation of conductive channels between the repository and the ground surface, passages through hydraulic conductor domains (HCDs) shall be mechanically and hydrologically separated from closure that limits advective transport.	Below the location of the top seal, the integrated effective connected hydraulic conductivity of the backfill in tunnels, ramp and shafts and the EDZ surrounding them must be less than 10^{-8} m/s. This value need not be upheld in sections where e.g. the tunnel or ramp passes highly transmissive zones (Requirement SRCAN178). Boreholes must be sealed such that they do not unduly impair the containment or retention properties of the repository. This is preliminarily achieved if the hydraulic conductivity of the borehole seal < 10^{-8}m/s, which is ensured if the swelling pressure of the seal is > 0.1 MPa. This value need not be upheld in sections where e.g. hole passes highly transmissive zones (Requirement SRCAN191).
DRCL23	The closure material in the main tunnel shall, at the installed density, provide sufficient restraint to restrict the swelling/expansion of the backfill so that the backfill's barrier functions are not significantly impaired.	
DRCL24	Closure material used in the rock caverns of the central area and top sealing shall remain in place in the final repository and not diminish significantly in volume.	
DRCL25	The mechanical properties of the top seal shall be such that excavation applying currently known technique entails considerable effort.	
DRCL27	The mechanical properties of the closure in the underground openings in the central area shall be such that it prevents significant convergence of surrounding rock walls and subsidence in the surrounding rock.	

ID	Requirements level 4: Design requirements, closure*	Linked design premise from "Design premises, long-term safety"
DRCL26	The composition and density of the installed closure material shall be such that its functions are upheld and retained for a long time.	
DRCL35	The closure material may not contain substances that may impair the barrier functions of the rock or the engineered barriers.	
Requirements from other engineered barriers		
DRCL28	Requirements from other engineered barriers concern requirements related to technical feasibility. There are no such requirements imposed on the closure by the other engineered barriers.	
Requirements related to production and operation		
DRCL32	The closure materials shall be possible to compact to the required density.	
DRCL33	Closure components (e.g. blocks and pellets) shall be designed so that installation can be carried out with high reliability.	
Requirements made by the closure on other engineered barriers and underground openings		
DRCL29	The stipulated design requirements and design premises for the closure are based on that the other engineered barriers and the underground opening fulfil the requirements that are imposed on them. Some principles are summarised below.	
DRCL30	For the density of the installed closure to remain over the lowest acceptable, constraint must be exerted by plugs and closure in adjoining underground openings so that the closure material is neither transported nor – in underground openings filled with swelling clay – swells / expands out of the closed underground opening.	
DRCL31	In order that the closure in underground openings filled with swelling clay should fulfil requirements on density and density distribution, the water inflow into the underground openings and their geometry and irregularities in them must be known and limited.	

* The official requirements are written in Swedish, the presented translations are unofficial.

In addition to the design requirements and their linked design premises reported in the table above, the following design premises with relevance to design and development of the closure are stipulated in Design premises, long-term safety:

- There is no restriction on the hydraulic conductivity in the central area (requirement SRCAN223).
- Only low pH (< 11) materials are allowed below the level of the top seal (requirement SRCAN184).
- Other foreign materials must be limited – but the amounts considered in SR-Can are of no consequence (requirement SRCAN185).

In the approved version of design requirements for closure, no link has been made to these design premises. For (requirement SRCAN223), which applies to hydraulic conductivity in the central area, a possible link is from requirement DRCL24, which stipulates what properties the closure in the central area's rock caverns shall have. The design premises (requirement SRCAN184 and SRCAN185) can be linked to requirement DRCL35, which stipulates that the closure material may not contain substances that can significantly degrade the barrier functions of the rock or the engineered barriers.

Requirement table

The Nuclear Fuel Programme’s requirements database

Module prefix, requirement ID	Module name, version number (suffix)
DRCL*requirement ID* *Requirement ID* = 14–15, 17–37	Design requirements, closure, 1.0 (Application 2011)
SRCAN*requirement ID* *Requirement ID* = 178, 179, 184, 185, 191, 210, 223	Design premises, long-term safety, 1.0 (Application 2011)