Strål
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Swedish Radiation Safety Authority

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Technical Note

2015:06

Feasibility of Backfilling Deposition Tunnels

Main Review Phase

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SSM perspektiv

Bakgrund

Strålsäkerhetsmyndigheten (SSM) granskar Svensk Kärnbränslehantering AB:s (SKB) ansökningar enligt lagen (1984:3) om kärnteknisk verksamhet om uppförande, innehav och drift av ett slutförvar för använt kärnbränsle och av en inkapslingsanläggning. Som en del i granskningen ger SSM konsulter uppdrag för att inhämta information och göra expertbedömningar i avgränsade frågor. I SSM:s Technical note-serie rapporteras resultaten från dessa konsultuppdrag.

Projektets syfte

Det övergripande syftet med projektet är att ta fram synpunkter på SKB:s säkerhetsanalys SR-Site för den långsiktiga strålsäkerheten för det planerade slutförvaret i Forsmark. Denna rapport diskuterar SKB:s redovisning av referensutformning och säkerhetsfunktioner för återfyllnaden, och utreder genomförbarhet av SKB:s föreslagna lösningar för återfyllnadens tillverkning, installation och provning.

Författarens sammanfattning

SKB har genomfört ett lämpligt forsknings- och utvecklingsarbete ur ett vetenskapligt och tekniskt perspektiv för att undersöka de många processer som kan påverka valet av återfyllnadsmaterial, de praktiska frågorna om installation av återfyllnaden, och egenskaperna hos den installerade återfyllnad som kan påverka långsiktig säkerhet av slutförvaret. Utifrån detta forsknings- och utvecklingsarbete har SKB tagit fram procedurerna för återfyllning av deponeringstunnlarna.

SKB:s forsknings- och utvecklingsprogram har identifierat och utrett, men ännu har inte åtgärdat alla potentiella praktiska svårigheter som kan uppstå i de olika återfyllningsprocesserna. En viktig fråga bland dessa svårigheter är inverkan av vatteninflödet intill deponeringstunnlarna på återfyllnadsmaterial under installation (t.ex. kanalbildningserosion, vätning av tunnelbotten). Omfattningen och betydelsen av svårigheterna beror väldigt mycket på slutförvarsmiljön under drift av slutförvarsanläggningen (t.ex. vatteninflödet).

Hastigheten för installation av återfyllnadsblock är en annan viktig faktor som ytterligare bör beaktas. Vidareutveckling skulle också behövas för att testa metoderna för pressning av de största återfyllningsblock som ingår i referensutformningen, där tidigare erfarenheter saknas. Det kan vara fördelaktigt att fortsätta förbättra metoderna för installation av återfyllnadsblocken.

Det finns ett tydligt behov av dokumentation av detaljerade förfaranden för kontroll och styrning av installation av återfyllnaden, och dessa bör omfatta metoder för att hantera de praktiska svårigheter som kan uppstå. Det finns också ett tydligt behov av fullskaliga, underjordiska och ingenjörsmässiga demonstrationer av genomförbarhet av återfyllningsprocesserna, för att utreda det eventuella vatteninflödet till deponeringstunnlarna vid Forsmark, samt för att fastställa vilken återfyllningstakt som tillförlitligt kan uppnås samtidigt bibehålla lämplig kvalitet. Långsiktiga försök för att mäta svälltryck och hydrauliska konduktivitet hos de kompakterade återfyllnadsmaterialen bör också övervägas. Sådana försök skulle kunna genomföras i en inledande del av ett slutförvar i Forsmark.

Projektinformation

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Diarienummer ramavtal: SSM2011-3392
Diarienummer avrop: SSM2013-3338
Aktivitetsnummer: 3030012-4058

SSM perspective

Background

The Swedish Radiation Safety Authority (SSM) reviews the Swedish Nuclear Fuel Company's (SKB) applications under the Act on Nuclear Activities (SFS 1984:3) for the construction and operation of a repository for spent nuclear fuel and for an encapsulation facility. As part of the review, SSM commissions consultants to carry out work in order to obtain information and provide expert opinion on specific issues. The results from the consultants' tasks are reported in SSM's Technical Note series.

Objectives of the project

The general objective of the project is to provide review comments on SKB's postclosure safety analysis, SR-Site, for the proposed repository at Forsmark. This technical note discusses the proposed design and functions of the backfill, and examines the feasibility of SKB's proposed solutions for backfill manufacture, installation and testing.

Summary by the author

SKB has been conducting an appropriate scientific and technical programme of research and development work to investigate the many processes that may affect the choice of backfill materials, the practicalities of backfill emplacement, and the properties of the emplaced backfill that may affect long-term radiological safety. On the basis of this research and development work SKB has outlined a process for backfilling the repository deposition tunnels.

SKB's research and development programme has identified and addressed, but not yet resolved various potential practical hindrances that may affect the backfilling process. Principal amongst these potential practical hindrances are the effects of water inflow to the repository tunnels on the backfill materials during the backfilling operations (e.g. piping and erosion, wetting of the backfill bottom bed). The magnitude and significance of these hindrances will depend very much on the conditions (e.g. of water inflow) encountered underground in the repository.

The rate of backfilling that can be achieved is another key factor that will require further consideration. Further work would also be needed to develop and/or obtain and test presses for the production of the largest backfill blocks in the reference design, which lie above the range of current experience. It may be beneficial to continue investigating improved methods for backfill block emplacement.

There is a clear need for the development and documentation of detailed procedures with which to control the backfilling operations and these should include methods for mitigating the possibly significant practical hindrances that may be encountered.

There is also a clear need for full-scale underground engineering feasibility trials of the backfilling process to demonstrate the feasibility of the backfilling operations, to assess the actual rates of water inflow to the repository tunnels at the Forsmark site, and to determine the rates of backfilling that can be reliably achieved while still maintaining suitable quality. Long-term tests and experiments to measure the swelling pressures and hydraulic conductivities of emplaced backfill materials should also be considered. Such trials and tests might be commissioned in an initial portion of a repository at the Forsmark site.

Objectives of the project

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Contents

Summary

The Swedish Radiation Safety Authority (SSM) is reviewing a license application, which has been submitted by Swedish Nuclear Fuel and Waste Management Co. (SKB), for a spent nuclear fuel repository at Forsmark.

This technical note records the findings from a project that forms part of the main phase of SSM's license application review. The project was undertaken on behalf of SSM by TerraSalus Limited.

The project involved review of reports on issues related to the installation and initial state of the bentonite clay backfill materials that SKB proposes to use to fill the waste deposition tunnels in the repository.

The technical note discusses the proposed design and functions of the backfill, and examines the feasibility of SKB's proposed solutions for backfill manufacture, installation and testing.

In brief, the review suggests that SKB's research and development programme has identified and addressed, but not yet resolved various potential practical hindrances that may affect the backfilling process. Principal amongst these potential practical hindrances are the effects of water inflow to the repository tunnels on the backfill materials during the backfilling operations (e.g. piping and erosion, wetting of the backfill bottom bed). The magnitude and significance of these hindrances will depend very much on the conditions (e.g. of water inflow) encountered underground in the repository.

There is a clear need for full-scale underground engineering feasibility trials of the backfilling process to demonstrate the feasibility of the backfilling operations, to assess the actual rates of water inflow to the repository tunnels at the Forsmark site, and to determine the rates of backfilling that can be reliably achieved while still maintaining suitable quality. Long-term tests and experiments to measure the swelling pressures and hydraulic conductivities of emplaced backfill materials for the new backfilling concept should also be considered. Such trials and tests might be commissioned in an initial portion of a repository at the Forsmark site.

1. Introduction

1.1. SSM's Review

The Swedish Radiation Safety Authority (SSM) is undertaking a formal review of a License Application, which has been submitted by Swedish Nuclear Fuel and Waste Management Co (SKB) for construction, possession and operation of a spent nuclear fuel repository at Forsmark. SKB's Application includes a safety assessment known as SR-Site (SKB 2010a, TR-11-01).

SSM is conducting its review in phases. The initial phase of SSM's review has been completed and SSM has concluded that SKB's reporting is sufficiently comprehensive and of sufficient quality to justify a continuation of SSM's review to the main review phase. Based on issues identified during the initial review phase, SSM has defined and prioritized a set of review assignments that will be undertaken during the main review phase. The intention is that these main phase review assignments should indirectly or directly support SSM's compliance judgements and the establishment of any necessary Licence Conditions.

SSM regards the main phase review assignments an essential and necessary basis for the licensing review. It is not the role of individual review assignments, however, to explicitly evaluate compliance in relation to any part of SSM's regulations or guidelines, because the determination of compliance is one of SSM's key over-arching responsibilities in the licensing review.

This technical note records the findings from a main phase review assignment undertaken on behalf of SSM by TerraSalus Limited. The review assignment has focussed on the feasibility of backfilling deposition tunnels.

In more detail, the objectives of the review assignment included considering the following questions and feasibility issues:

- Are there any foreseeable practical hindrances during backfilling that may make it difficult to achieve the desired initial state of the backfill?
- Is SKB's reporting on the issues sufficiently scientifically and technically sound?
- Can SKB's reporting on measures to be taken during backfilling and/or further development of techniques to overcome hindrances be judged in principle as being reliable from a scientific and technical basis?
- Are there any large practical hindrances that are in principle difficult to overcome or that may need a very long time (on the order of decades) to further develop techniques to overcome?

The scope of the review assignment related to 'normal' operating conditions within the repository. An assessment of 'accident' conditions (e.g., fire, flooding, rock fall) was outside the scope of this particular review assignment.

1.2. SKB's Concept

Based on several decades of research and development work, SKB is proposing to develop a repository for the final stage of spent nuclear fuel management according to the KBS-3 method. The purpose of the KBS-3 repository would be to isolate the nuclear waste from man and the environment for very long times. Around 12,000 tonnes of spent nuclear fuel is forecast to arise from the currently approved Swedish nuclear power programme, corresponding to roughly 6,000 canisters in a KBS-3 repository (SKB 2010a, TR-11-01).

In the KBS-3 method, copper canisters with a cast iron insert containing spent nuclear fuel would disposed of within a bentonite clay buffer at approximately 500 m depth in groundwater-saturated, granitic rock. Bentonite clay includes a mineral called montmorillonite that swells as it becomes saturated with water. The materials for the buffer are selected and emplaced in the repository so that the buffer will develop physico-chemical properties (e.g. swelling pressure, hydraulic conductivity, density) within a certain desired ranges.

The repository would comprise an array of horizontal waste deposition tunnels. The copper canisters containing the waste would be placed into vertical boreholes drilled in the floor of the tunnels.

After waste canister and buffer emplacement, the tunnels would be backfilled. The tunnel backfill has several important roles. For example, the backfill needs to be emplaced soon after waste and buffer emplacement to prevent the buffer materials swelling too much upwards into the tunnels and thereby becoming less dense. To do this the backfill must have certain physico-chemical properties (e.g., density). The backfill also needs to develop an appropriate hydraulic conductivity and have a chemical composition that is compatible with the other engineered barriers in the disposal concept. For example, the backfill should not include substances (chemicals) in amounts or concentrations that might cause a problem, such as by being too corrosive towards the copper canister. Details of the desired properties of the backfill and the plans for backfilling and testing of the backfill are discussed and evaluated below.

The reference concept reported by SKB is that the backfill consists of compacted bentonite clay blocks and pellets to be installed in the deposition tunnel (SKB 2010b, TR-10-16, page 24). The bentonite clay materials should have a nominal montmorillonite of content of 50-60 wt %, with an acceptable variation within 45-90 wt %. Moreover, at least 60 % of the tunnel's volume should be backfilled with blocks and the rest with pellets (SKB 2010b, TR-10-16, page 5).

2. Backfill Production Line

This section considers each of the various steps that comprise SKB's production line for the backfill. Section 2.1 summarises the steps in the production line based on SKB's reporting (see in particular SKB 2010b, TR-10-16). Section 2.2 describes the motivation for SSM's assessment of backfill feasibility, and Section 2.3 presents the results of the assessment.

2.1. SKB's presentation

2.1.1. Backfill Safety Functions

The safety functions defined by SKB for the backfill are illustrated in Figure 2.1. The defined safety functions of the backfill are to:

- Counteract buffer expansion.
- Limit advective transport of radionuclides.
- Sorb radionuclides.

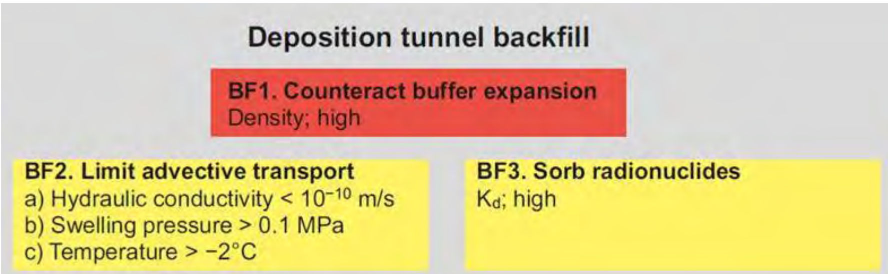

Figure 2.1 SKB's backfill safety functions (from SKB 2010a, TR-11-01)

Figure 2.1 shows more details of the properties that the backfill material should possess (e.g., densities, hydraulic conductivities, swelling pressures) in order to fulfil the safety functions. In particular, the hydraulic conductivity of the backfill should be < 10^{-10} m/s, and the swelling pressure should be > 0.1 MPa. To achieve these properties, it is important to install the backfill with a sufficiently high density. The density of the material may also affect other potentially important processes, including the activity of microbes and the reduction of sulphate to sulphide, which can be corrosive to the copper canister.

2.1.2. Backfill Design

The reference design for the backfill is illustrated in Figure 2.2, and comprises a range of blocks, discs (for the top of the deposition holes) and pellets of compressed bentonite that would fill the tunnel space above the buffer.

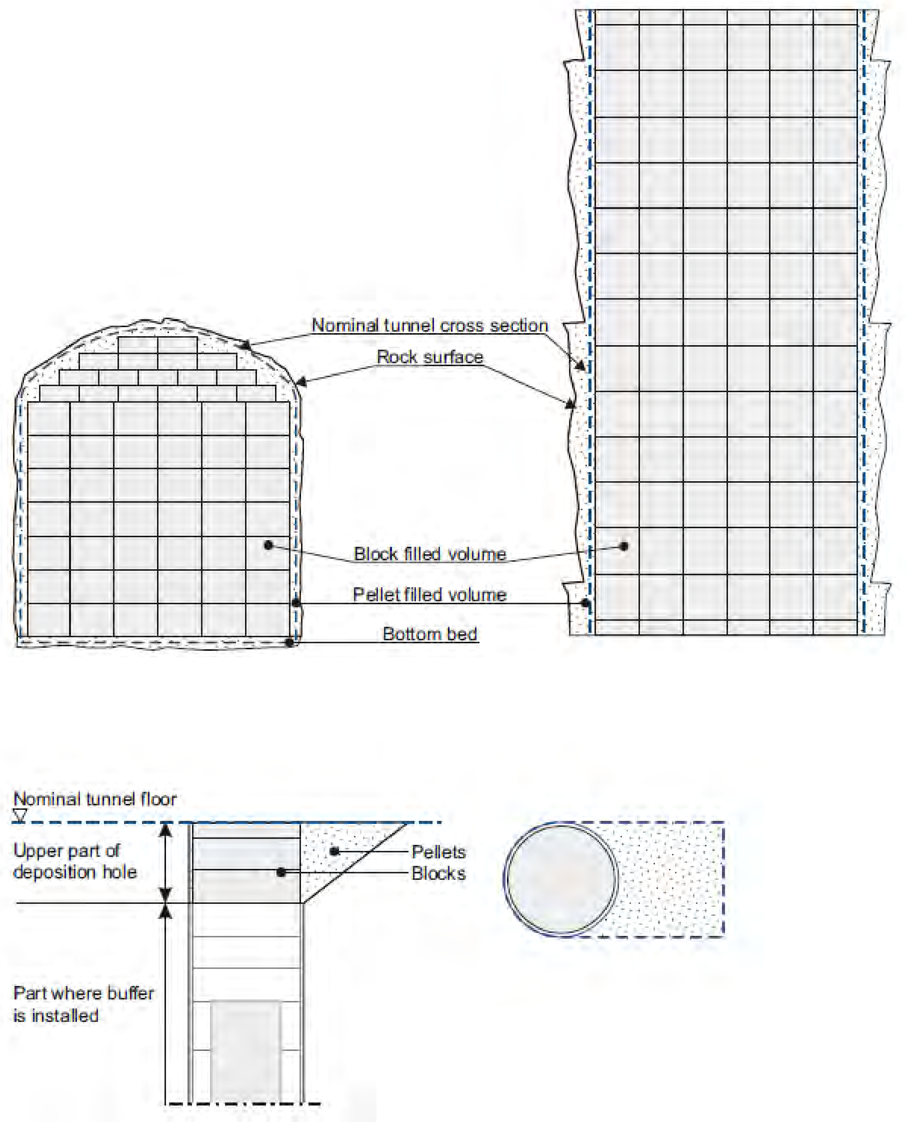

Figure 2.2 Reference design of the backfill (from SKB 2010b, TR-10-16)

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2.1.3. Backfill Materials

The reference material for the backfill is based on bentonite clay. SKB suggests that the reference composition should contain between 50 and 60 % montmorillonite, but that this range might in future be widened (relaxed) (SKB 2010b, TR-10-16). SKB

(2010b, TR-10-16, page 33) suggests that smectite-rich mixed layer clays or mixtures of bentonite and ballast might be used. The example backfill material considered in SR-Site is the calcium and magnesium-rich Milos BF 04 bentonite.

2.1.4. Backfill Production Line

Figure 2.3 shows SKB's flowchart for the production of the backfill. The production line for the backfill comprises the following three main parts:

- Excavation and delivery.
- Manufacturing of blocks, pellets and bottom bed material.
- Handling and installation.

The following sections briefly describe each of the steps in the process.

SKB (2010b, TR-10-16) discusses the level of practical experience that existed at that time for each of the steps in the production line and also identifies opportunities and plans for inspection of the backfill production process at each stage. Supporting references to SKB (2010b, TR-10-16) describe various tests and trials of backfill manufacture (e.g. Wimelius and Pusch 2008; Keto *et al*. 2009); these are addressed in Section 2.2 of this report.

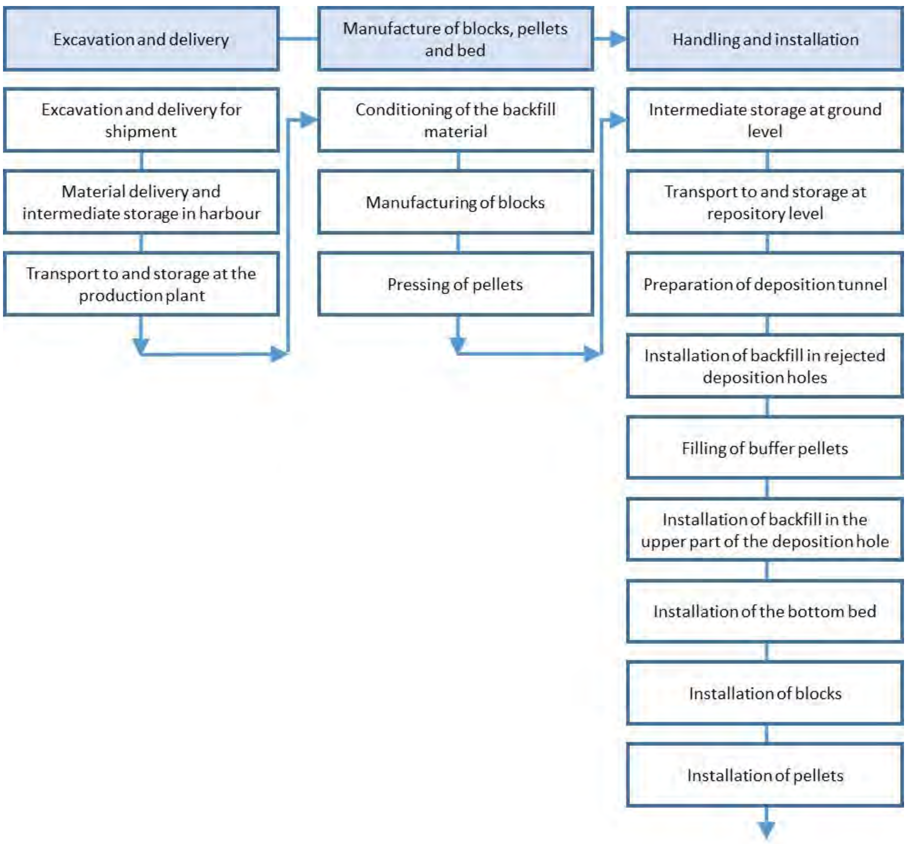

Figure 2.3 SKB's flowchart for backfill production (after SKB 2010b, TR-10-16).

Excavation and delivery

SKB plans to order *'low-grade'* bentonite for use as backfill from one or more commercial bentonite suppliers (SKB 2010b, TR-10-16). The commercial bentonite suppliers would carry out the excavation and primary characterisation of the materials. SKB plans to develop and implement a procedure for qualification of suppliers.

The bentonite would be delivered from self-unloading ships to a harbour close to the repository site. If the bentonite is accepted, it would be unloaded and transported to a storage building. Enough material would be delivered so as not to interrupt the backfill production process even if a particular delivery was not to be accepted. In the storage building the temperature would be kept above 0°C and the humidity would be regulated so that condensation would be avoided.

After acceptance, the material would be transported by truck to the production plant reception building at the repository site. To avoid wetting and provide good working conditions, the loading area would be indoors and provided with controlled ventilation. The material delivered from different shipments would be kept separate.

Manufacture

Conditioning of the backfill material would involve processing of the material to specific granule size distributions and water contents. The process for conditioning the material comprises the following activities:

- Drying to a water content suitable for grinding.
- Grinding in a hammer mill to a granule size suitable for compaction.
- Storage of ground material.
- Wetting of ground material in mixers to a water content suitable for compaction.
- Storage of material ready for compaction.

The reference method for manufacturing of backfill blocks is uniaxial compression of individual blocks in a press. The block press has a fixed lower die, a moveable upper die and a moveable mould frame. The density of the blocks produced depends on the granule size distribution and water content of the material to be compressed, and on the compaction pressure.

The dimensions of the blocks are determined by the dimensions of the mould and the amount of material placed in the mould. The mass of material placed in the press must be accurate in order to obtain the required block dimensions. The backfill material is, therefore, weighed before it is placed in the press. In order to get homogenous blocks and avoid air entrapment and lamination problems, the press is fitted with an evacuation device. In order to reach the required capacity, SKB's plan is to have two presses and an automated process with a system for the control of the filling of the pressing tool, feeder belt and handling of blocks and pallets.

In the reference design, the same type of pellets are used for the bottom bed, for filling the gap between the blocks and the rock wall in the deposition tunnel and for filling the bevel in the upper part of the deposition hole. The reference method for manufacturing of the pellets is roller compaction. The machine for manufacture of the pellets consists of a screw and two rolls. By adjusting the machine it is possible to select the size and density of the pellets.

Handling and installation

Prior to transport to the repository level, the blocks and pellets would be stored on the surface within the repository compound. The properties of blocks and pellets must not be altered during handling and transport. The shape of the blocks must not be altered and they must not be exposed to shocks that create fractures. It is also important that the water content of the blocks and pellets is not changed during storage. For these reasons SKB proposes to store the blocks on specially designed pallets, at reduced pressure under diffusion-tight plastic covers. The pellets would also be stored in diffusion-tight containers.

SKB plans to transport the block and pellets to the repository level in skips. To achieve the prescribed installation rate, approximately 40 pallets of blocks and 15 containers of pellets would need to be transported each day (SKB 2010b, TR-10-16).

Preparation of the deposition tunnels for backfilling would include:

- Inspecting the walls of the tunnels. Scaling and rock bolting would be undertaken as necessary.
- Cutting of any roof bolts that lie within the nominal cross section of the tunnel.
- Cleaning of the tunnel and removal of equipment from earlier activities.
- Cleaning and removal of gravel and other materials from the tunnel bottom.
- Measuring of water inflow to the tunnel.
- Scanning of the rock walls to determine the tunnel volume, the tunnel contour and the geometry of the bevel.
- Installation of temporary ventilation, electric supplies and lighting.

Before installation of the backfill in deposition tunnels proceeds, any rejected deposition holes would be backfilled. SKB 2010b, TR-10-16 states that *'the material and technique for this will be determined before the deposition of canisters commences, and can be similar as for the buffer or backfill'*.

If there are deposition holes in the section of the tunnel to be backfilled, the installation of the buffer must be finished and the upper part of the deposition holes backfilled before the installation of the backfill bottom bed, blocks and pellets commences. The two top blocks in the deposition hole are considered to be part of the backfill. However, in the current reference design they are made of the same material as the buffer and they are deposited at the same time as the buffer.

The reference method for installation of the bottom bed is to use a screw feeder and compaction equipment to compact the material. The bottom bed has to be compacted and the flatness of the surface adjusted; SKB plans to use a vibratory plate tool for this purpose.

The reference method for installation of blocks is the '*block method*', which implies individual emplacement of each block with a block installer machine. To follow the contour of the tunnel, two sizes of backfill blocks are used. An example of how block placement may be carried out is illustrated in Figure 2.4. The backfill blocks would be placed on a conveyor that brings the blocks to a position where a lifting tool grabs the blocks and lifts them into their position in the tunnel. The blocks would be installed one by one from side to side of the deposition tunnel until a complete vertical layer is installed.

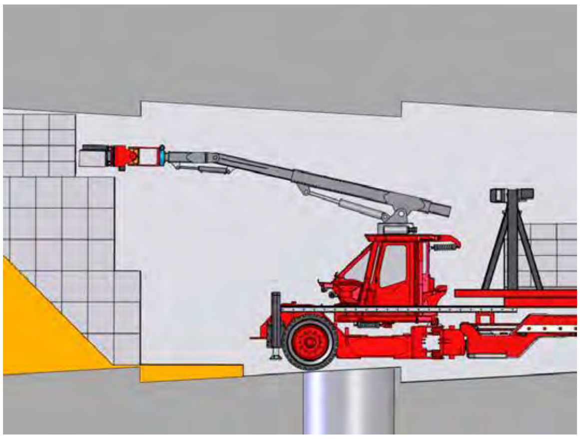

Figure 2.4 Illustration of backfill block emplacement (from SKB 2010b, TR-10-16).

The reference method for installation of the pellets around the blocks is to inject the pellets into the spaces between the backfill blocks and the tunnel walls using dry spraying equipment.

To prevent dust small amounts of water may be added during the installation of the pellets. The installation equipment proposed is illustrated in Figure 2.5 and comprises a carrier with a beam in front that can be rotated and folded into different positions. Mounted in front of the beam is a lance with a tube designed to reach into the narrow spaces between the blocks and the rock and to have capacity to achieve the prescribed installation rate.

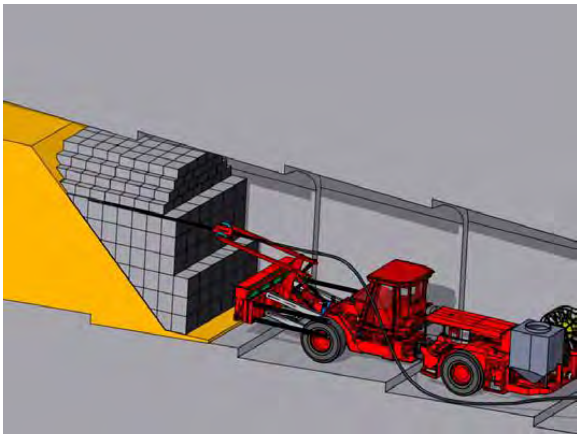

Figure 2.5 Illustration of backfill pellet emplacement. The pellets are shown in yellow (from SKB 2010b, TR-10-16).

In the reference procedure the deposition tunnel would be backfilled section by section. Since the vehicles used for the installation must not drive on the bottom bed, the length of each section would be determined by the reach of the block installation equipment.

2.2. Motivation for SSM's assessment

SSM's preparation for the Licence Application review has necessarily included tracking SKB's research and development work and proposals for the backfill over several years (e.g., Bennett 2004; 2007; 2010; 2012, Savage *et al*. 2008). During this period the concept and design for backfilling the deposition tunnels has been revised several times, in response to findings from laboratory studies and more in-depth analysis of the backfill's long-term safety functions.

The reference concept reported by SKB in its Backfill Production Report (SKB 2010b, TR-10-16) and summarised above is, thus, relatively new and laboratory studies of its development and demonstrations of the backfilling processes are relatively fewer compared to those for the other engineered barriers in the KBS-3 repository. In addition, SSM's preparations and initial reviews have identified several potential practical difficulties that might affect the backfilling process, as well as some questions regarding demonstration of the ability of the backfill to provide the desired safety functions.

If the repository is to be licenced, constructed and used for waste disposal, it will be essential for there to be sufficient confidence in many aspects, including in the feasibility of the backfill concept. In coming to a view on the confidence that exists, it will be necessary to consider the properties of the backfill materials and various practical considerations, given the conditions (e.g. of water flow) that may be experienced underground in the repository.

It will also be important that there is confidence that the backfill installed in the repository, which will quite possibly have various non-idealities or imperfections as compared with the theoretical concept, will actually achieve the required initial state assumed in the long-term safety assessment and will, thus, contribute to providing long-term radiological safety in the manner envisaged by SKB.

2.3. Assessment

Based on review of SKB's reports and other published materials (e.g., in the literature and from relevant investigations in the Finnish programme for the disposal of spent fuel using the KBS-3 method e.g. Posiva 2012a and references therein), as well as experience in tracking SKB's programme for the last decade or more, including visits to SKB's clay laboratory and other facilities at Äspö, this section identifies and discusses foreseeable practical hindrances during backfilling. The section also comments on SKB's reporting on measures that could be taken during backfilling to overcome such hindrances. In particular, the section highlights practical hindrances that may either make it difficult to achieve the desired initial state of the backfill or that may be difficult to overcome or need a very long time (on the order of decades) to overcome.

2.3.1. Backfill Materials

Over recent years SKB has proposed the use of backfill materials containing successively greater proportions of swelling clay (montmorillonite). This progressive change in the choice of backfill material has come in response to findings from various experiments and estimations of the proportion of tunnel volume that it would be practical to fill with backfill blocks, which together have suggested that it may be difficult to achieve sufficiently high swelling pressures and/or sufficiently low hydraulic conductivities with backfills containing lower amounts of swelling clay (e.g., Keto *et al.* 2009, R-09-52). Having followed this development process, it is considered that SKB's proposals in SKB (2010b, TR-10-16) for the backfill materials are in principle appropriate, with one exception.

The exception is the possible use of backfills indicated in SKB 2010b, TR-10-16 composed of mixtures of bentonite and ballast (crushed rock). The use of such mixed backfills is questioned because it seems not to take full account of previous experimental results (e.g., from the Backfill and Plug test at the Äspö hard rock laboratory) that suggested that it may not be able to achieve sufficiently low hydraulic conductivities with such mixtures (e.g., Keto *et al.* 2009, R-09-52). The indication in SKB 2010b, TR-10-16 that backfills composed of mixtures of bentonite and ballast are still a possibility is, therefore, surprising as it seems to contradict previous statements by SKB on such mixed backfill materials. For example, Keto *et al.* (2009, R-09-52, page 118) state, '*All of the backfill block materials studied,* ***excluding the mixture of bentonite and ballast (30:70)****, are suitable candidates for backfilling using the block-pellet concept. The 30/70 mixture was excluded mainly due to its apparently limited self-sealing capacity but also due to low safety margin compared to other material alternatives'*.

Secondary points about the proposed backfill material (SKB 2010b, TR-10-16) are that:

- The specified acceptable variation of montmorillonite of content (45-90 weight %) has a rather broad range, which if realised in practice could lead to backfills in different parts of the repository having quite different properties.
- Continuing research may be needed in the area of the levels of potentially detrimental (e.g., corrosive) 'impurities' in the backfill materials and the presence and possible activity of sulphate reducing microbes (e.g. Posiva 2012b).

2.3.2. Backfill Production Line

Excavation and delivery

SKB (2010b, TR-10-16) describes the initial stages of the backfill production line and points to the good level of industrial capability and experience that exists with respect to the excavation and supply of bulk bentonite materials. Bentonite deposits exist at many places around the world and a range of commercial bentonite suppliers is available. SKB itself has some experience, including the purchase and receipt of the commercial bentonite product MX-80 from the American Colloid Company. The application of appropriate quality assurance measures (e.g., to assure appropriate bulk materials compositions and avoid too high amounts of impurities) should, in principle, be able to ensure supplies of suitable raw materials for the later stages of the backfill production line. No significant practical concerns that may affect the initial state of the backfill in the repository have been identified, particularly because later stages in the production line involve further checks and processes for conditioning the materials to the required granule size distributions and water contents.

Manufacture

SKB's experiences related to the manufacture of backfill pellets and blocks are outlined in Section 5.3.7 of SKB (2010b, TR-10-16). The technique for pressing of pellets has been tested at two suppliers; BEPEX-Hoskawas in Germany and Sahut-Conreur SA in France. SKB's conclusion is that the technique for pellet manufacture is well known from other industrial applications and has been used for production of pellets for the field tests in the Äspö hard rock laboratory.

Backfill block manufacturing has been performed with different materials (e.g., Milos, Asha 230, IBECO-RWC-BF and Friedland clays) and block sizes (up to 300×300×150 mm). SKB's conclusion is that the pressing of blocks from bentonite material is a well-tried and reliable method. The results depend on a number of adjustable parameters, and the pressing process will need to be adjusted to the press and material in order to ensure a reliable process delivering blocks within the accepted tolerances.

This review has not identified any major concerns with the manufacture of the pellets or the blocks, but further work would be needed to develop and/or obtain and test presses for the production of the largest backfill blocks in the reference design, which are up to 700×667×510 mm in size and lie above the range of current experience.

It is important to understand that the process of backfilling a repository would need to be conducted at a certain rate and that the required rate is linked to the rate of canister and buffer deposition. Part of the reason for this is because if the KBS-3 bentonite buffer is not physically restrained in the deposition hole, it will swell, or 'heave', upwards into the deposition tunnel on a timescale of hours to days and lose density (e.g., Åberg 2009, R-09-29). This loss of buffer density could be significant to long-term safety because having a density within a specified range is one of the key properties of the buffer that affects the achievement of its safety functions. Of course, if it were allowed to occur, significant movement of the buffer upwards into the deposition tunnels prior to backfilling would also disrupt the backfilling process.

Another reason why the rate of backfilling is important, derives from the fact that tests have shown that it is critical to provide a clay block backfilling system with lateral support and confinement as quickly as possible following block installation.

Exposure of the blocks to even low rates of water ingress can result in rapid loss of block cohesion and subsequent slumping of the block materials into the spaces between the blocks and the tunnel walls (Dixon *et al.* 2008b, R-08-134).

SKB (2010b, TR-10-16) recognises the need to avoid situations in which the supply of backfill materials to the repository is interrupted or delayed significantly, but the descriptions of SKB's plans for providing sufficient capacity for backfill manufacture do not appear to include provision of sufficient redundancy in backfill manufacturing equipment. This deficiency should not affect the safety of the disposal system, however, because details of the backfill production line (e.g. the provision of additional mixers or presses to allow for machine maintenance schedules or failures) should easily be resolved prior to waste emplacement.

Handling and installation

Logistics

It is clear from SKB's Production Line reports for the backfill and buffer (SKB 2010b, TR-10-16; 2010c, TR-10-15 – see also Keto *et al.* 2009, R-09-52 and Wimelius and Pusch 2008, R-08-59) that a complex sequence of activities will need to be undertaken in the deposition tunnels in preparation for and during backfilling. Given that the components of the engineered barrier system would need to be installed at a certain rate, the logistics of these activities will need to be considered more fully and described in more detail. Sufficient time should be included for checking the quality of the installed components and the accuracy of their emplacement, for independent inspections, and for any corrective measures that may need to be undertaken.

Backfill transport and emplacement underground

As discussed elsewhere in this report, in order to achieve the desired backfilling rate it would be necessary to transport considerable quantities of bentonite to the repository level and the backfilling face(s) in the deposition tunnels each day. The Backfill Production Line report (SKB 2010b, TR-10-16) indicates that transport of the backfill materials would be conducted using skips, pallets and containers, but gives few details. This review has not identified any fundamental practical problems with the approach described, but it is noted that more detailed considerations of alternative and potentially more beneficial transport methods have been made within SKB's research programme. For example, several options for the transport of backfill blocks were considered by Wimelius and Pusch (2008, R-08-59), some of which may have the potential to lead to improved methods for backfill block emplacement.

Wimelius and Pusch (2008, SKB R-08-59) described three potential methods for placing of the backfill blocks; the Block method, the Robot method, and the Module method. The Block method which has been described as the reference method in SR-Site, would involve individual handling and placement of backfill blocks. This is relatively tedious and may cause unacceptable delays in backfilling rate if even minor disturbances occur (Wimelius and Pusch 2008, SKB R-08-59). The Robot method would provide fully automatic handling of the backfill blocks, but would require a unique system design that remains to be developed and tested. Wimelius and Pusch (2008, SKB R-08-59) suggests that the Robot method might be difficult to apply in combination with other necessary backfilling activities, such as the removal of the buffer protection sheets (see SKB 2010, TR-10-15), installation of pellets and adjustment of foundation beds. The Module method would involve the emplacement of pre-assembled stacks of clay blocks using a fork-lift truck. This method would also require manufacture of a range of different shaped and sized backfill blocks. The Block method and the Robot method would rely on a vacuum technique for lifting and handling the blocks, which brings relatively greater risks of operational mishap than the use of fork-lift trucks (Wimelius and Pusch 2008, SKB R-08-59). Wimelius and Pusch (2008, SKB R-08-59) suggested in 2008 that the Block method could be adequately developed and tested before the end of year 2020, but that this date could not be met for the other two backfill block emplacement methods, which are less well developed and tested.

Efficiency of block filling

The proportion of the deposition tunnel that can be filled with backfill blocks is important because the blocks have a greater density than the pellets and, after re-saturation and homogenisation, the average bulk density of the backfill in the tunnel will be largely defined by this proportion and the density of the blocks. The deposition tunnels will be created by blasting and will have varying cross sections and shapes, because of the orientations of the blasting holes and the degree of breakout that occurs. SKB has assumed that it would be possible to fill 60% of the tunnel volume with blocks, but the actual proportion of blocks to pellets has yet to be measured in the underground. It may well be that a higher proportion of blocks to pellets can be achieved, but this would have to be demonstrated.

Water inflows, piping and erosion during backfilling

Water flowing into the repository may have various effects on the backfill. One of the primary concerns related to backfilling, especially in situations where backfilling operations may have been interrupted for a period of time beyond a few hours, is the potential for erosion of the backfill by water entering the deposition tunnel somewhere in the already backfilled region. Movement of water through the backfill has the potential to cause development of preferential flow paths (channels or pipes) and, at higher flow rates, significant physical erosion of the bentonite. Piping and erosion have been clearly observed in both large-scale tests (Figure 2.6; Dixon *et al.* 2008a, R-08-132; Dixon *et al.* 2011a, P-11-44), and many smaller-scale laboratory tests (e.g. those performed as part of the Baclo project – see Sandén *et al.* 2008).

Figure 2.6 Photograph of a 1/2-scale backfilling test performed at the Äspö hard rock laboratory showing backfill erosion caused by water inflow and movement in channels or pipes (from Dixon *et al*. 2011b).

The magnitudes of piping and erosion of the backfill clearly depend on the rate and pattern of water inflow to the deposition tunnel. Dixon *et al.* (2008a, R-08-132; 2011b, R-11-27) report that in their ½-scale experiments, little or no erosion occurred for inflow rates below approximately 0.1 litres/minute, but that disturbance of the backfill was likely for inflows via a single pathway at rates greater than approximately 0.25 litres/minute (e.g. Figure 2.6). Backfill disruption can also occur prior to installation of the mechanical plug at end of the deposition tunnel from the uncontrolled release of pressurized air pockets within the backfill (Dixon *et al.,* 2011b, R-11-27). Erosion of backfill from the pellet-filled regions would clearly in itself be a hindrance to further backfilling operations in the tunnel and may also lead to a reduction in the density of the backfill. Keto *et al*. (2009, R-09-52) discuss the possible need in some circumstances to remove and replace sections of disturbed backfill before new backfilling operations could start.

The degree of practical difficulty that occurs during subsequent backfilling operations may not, however, solely be related to the rate of water inflow from a single point source or from a single fracture that intersects the tunnel. Since water mostly flows close to the tunnel walls through the EDZ (Excavation Disturbed Zone) and the region filled with pellets towards the backfilling face, there may be an effect of tunnel length. The total amount of water arriving at the backfilling face may, thus, depend on the length of backfilled tunnel and this may increase with time as the length of backfilled tunnel increases during operations. The effect of the water arriving at the backfilling face could hinder or prevent installation of the bottom bed, a process that involves the placement and compaction of 'dry' bentonite pellets on the floor of the tunnel. In turn, difficulties with emplacement of the bottom bed could then affect or prevent the correct placement of further backfill blocks. These considerations highlight the potential need for water inflow management measures during backfilling operations. There may also be a need for further development and testing of methods for levelling and compaction of the bottom/foundation bed under realistic conditions.

Displacement of backfill blocks

Experimental tests indicate that if water enters the backfill system at a high enough rate then, rather than being rapidly taken up by the clay, some of the water may flow through channels or pipes in the pellet-filled regions and/or enter any gaps in the stacks of backfill blocks. It is important, therefore, that the backfill blocks are stacked accurately and that any gaps between the blocks are minimal because otherwise water pressure may force the blocks apart and affect the achievement of the desired initial state. Although in principle it should not be too difficult to closely stack bentonite blocks in an accurate manner, this does rely on there being a firm, flat and level bottom bed, and on there being sufficient time to cope with any other practical issues such as the collection of dust on blocks lower in the stack during operations. Again, therefore, it may be beneficial to continue investigating improved methods for backfill block emplacement such as those considered in Wimelius and Pusch (2008, R-08-59).

Backfilling Rate

As discussed above, the deposition tunnels would need to be backfilled soon (ideally within a few hours) after waste canister emplacement and the backfilling operations would need to be conducted at a certain rate so that the buffer has a chance of fulfilling its safety functions.

SKB 2010a, TR-10-16, page 70 states, '*The assessment after tests and studies is that the method [for backfill emplacement] is feasible but that it is dependent on advanced technology. The vacuum technique for lifting blocks needs to be tested more as well as the quality of the blocks in handling. In order to conform to the design premise to backfill a length corresponding to the average distance between deposition holes per day and considering the time consumption for other activities, the blocks have to be stacked within 60 seconds. In the tests this has been proven possible, but it presupposes that installation checking is frequently approved and that the water inflows do not affect the blocks until the pellets have been installed.' In order to support the conclusions and verify the performance of the technology, further full scale tests with pressed bentonite blocks will be performed.'*

It is noted that SKB 2010c (TR-10-13, pages 75-76) indicates total canister encapsulation rates of no more than 150 canisters per year for the period 2023 to 2070, which suggests that actual disposal rates might be slightly lower than one canister per day but, nonetheless, the timescales of perhaps 1 to 2 minutes for the emplacement of each backfill block in combination with a 24-hours per day, round-the-clock shift working pattern during backfilling seems ambitious. It is suggested, therefore, that further consideration needs to be given to methods for backfill block emplacement and the rate of backfilling and waste emplacement that realistically can be achieved under repository conditions in which there might be water inflows to the tunnels.

2.3.3. Full-scale backfilling tests

For the previous backfilling concept, which involved use of a mixture of granular clay and crushed rock, SKB conducted practical engineering trials of backfilling and made scientific measurements of backfill performance at full-scale in the underground at the Äspö hard rock laboratory (e.g. Gunnarsson *et al*. 2001; 2006). These trials and experiments were very informative, both from a practical perspective (e.g. in relation to revealing the difficulties of *in-situ* compaction of granular backfill materials) and from a technical perspective in terms of enabling measurements of backfill hydraulic conductivity. Indeed, the results obtained were a key part of reason for changing to the current backfilling concept involving pre-compressed bentonite blocks and pellets instead of granular backfill materials. Although the backfilling trials and experiments at Äspö were very helpful, the change in the backfilling concept means that there is a gap in the range of demonstrations and experiments for the disposal concept being proposed in the Licence Application and SR-Site, namely full-scale underground trials of the proposed backfilling concept and process. It is suggested that such practical engineering trials will be essential.

Potentially valuable objectives of such trials would include:

1) Demonstrating the feasibility of the backfilling operations and testing the procedures for backfilling.
2) Measuring the actual rates of water inflow to the repository tunnels at the Forsmark site. This may also yield information on processes such as piping and erosion.
3) Determining the proportion of the tunnel volume that it is practical to fill with backfill blocks - this has a direct effect on the density of the installed backfill, on the initial state of the backfill, and potentially on the selection of backfill materials.
4) Determining the rates of backfilling that can be reliably achieved while still maintaining suitable quality – this may influence the rates of waste disposal and of emplacement of the other engineer barriers.

It would be important for these trials to be performed at full scale and in the underground because some of the processes (e.g., relating to total water inflows and erosion) may not scale linearly from the smaller-scale trials conducted so far. It is important to conduct trials in the underground in order to gain experience of working in relevant conditions and to understand the actual water inflows and effects caused, for example, by the roughness of the tunnel walls and by any rock fractures intersected. In this respect the proposed trials must be considered at least as well justified as trials for the previous backfilling concept.

It might also seem sensible to attempt long-term full-scale experiments to measure backfill hydraulic conductivity and swelling pressures. However, it is not clear whether such experiments would be feasible given the reported ‘dryness’ of the rocks at Forsmark and the possibly long period that it might take for the current backfilling concept containing a high proportion of swelling clay to become hydrologically saturated. Artificial means for accelerating the hydration process were employed in some of the experiments conducted at Äspö, but it is not clear whether suitable approaches exist for a backfill comprising pre-compressed clay blocks; this, itself might need study. However, if it is possible to make representative measurements of backfill properties, particularly swelling pressure and hydraulic conductivity, at relevant scales in the period prior to first waste emplacement (perhaps over a few tens of years), then this might form be a sensible objective.

2.3.4. Pilot repository

It is entirely to be expected that a long-term testing and monitoring programme on repository science will continue throughout the life of a repository project as an integral part of the licensing processes consistent with statutory and regulatory constraints (e.g. Hansen 2012).

At different times over the last decade SKB in Sweden and Posiva in Finland have made statements about the possibility of defining an initial phase of repository construction and operation, in which only small proportion of waste canisters would be deposited. This would allow for monitoring of the situation with the hope that, over time, confidence would increase that the disposal operations and repository were proceeding and performing as expected.

SSM may wish to re-consider ideas such as permitting construction of an initial portion of a repository as a long term test and demonstration facility at the Forsmark site and possibly stipulating that the first disposal of waste be conditional on satisfactory demonstration that the proposed engineered barriers, including the backfill, can be emplaced at the required quality and rates.

2.3.5. Documentation and Procedures

SKB has described the production line for the backfill in TR-10-16. However, in general, the upper-level SR-Site reports do not provide a description or formal procedures that explicitly acknowledge the practical problems that might be encountered (especially during backfill installation underground). Neither do the upper-level SR-Site reports describe clearly mitigation measures that could be taken to overcome such practical problems.

The Production Line report (SKB 2010b, TR-10-16) explains how the backfill would be placed under ideal conditions, but does not discuss what would be done, for example, if a tunnel with higher than expected inflows of water were to be encountered. The supporting references to the backfill Production Line report are generally very well presented from a scientific and technical perspective and have identified many processes that may affect the practicalities and feasibility of the backfilling process. The supporting references have also often identified the potential need for the development of measures to mitigate practical difficulties, but the development and presentation of such measures does not seem to have been taken forward in the upper-level SR-Site documentation. There may, thus, be a gap in the information available, which would bridge between the design concepts and safety assessments, and the practical implementation of those concepts.

3. Overall assessment

SKB has been conducting an appropriate scientific and technical programme of research and development work to investigate the many processes that may affect the choice of backfill materials, the practicalities of backfill emplacement, and the properties of the emplaced backfill that may affect long-term radiological safety. On the basis of this research and development work SKB has outlined a process for backfilling the repository deposition tunnels.

SKB's research and development programme has identified and addressed, but not yet resolved various potential practical hindrances that may affect the backfilling process. Principal amongst these potential practical hindrances are the effects of water inflow to the repository tunnels on the backfill materials during the backfilling operations (e.g. piping and erosion, wetting of the backfill bottom bed). The magnitude and significance of these hindrances will depend very much on the conditions (e.g. of water inflow) encountered underground in the repository.

The rate of backfilling that can be achieved is another key factor that will require further consideration. Further work would also be needed to develop and/or obtain and test presses for the production of the largest backfill blocks in the reference design, which lie above the range of current experience. It may be beneficial to continue investigating improved methods for backfill block emplacement such as those considered in Wimelius and Pusch (2008, R-08-59).

There is a clear need for the development and documentation of detailed procedures with which to control the backfilling operations and these should include methods for mitigating the possibly significant practical hindrances that may be encountered.

There is also a clear need for full-scale underground engineering feasibility trials of the backfilling process to demonstrate the feasibility of the backfilling operations, to assess the actual rates of water inflow to the repository tunnels at the Forsmark site, and to determine the rates of backfilling that can be reliably achieved while still maintaining suitable quality. Long-term tests and experiments to measure the swelling pressures and hydraulic conductivities of emplaced backfill materials should also be considered. Such trials and tests might be commissioned in an initial portion of a repository at the Forsmark site.

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Coverage of SKB reports

Table A.1: Coverage of SKB Reports

Reviewed report	Reviewed sections	Comments
Design Production and Initial State of the Backfill and Plug in Deposition Tunnels, SKB Report TR-10-16	All	-
SKB, 2010. Design Production and Initial State of the Buffer, SKB Report TR-10-15	Particularly Section 5.4	
SKB, 2010. Spent Nuclear Fuel for Disposal in the KBS-3 Repository, SKB Report TR-10-13	Table C-3	
Åberg, 2009. Effects of Water Inflow on the Buffer – An Experimental Study, SKB Report R-09-29	All	
Dixon D., Anttila S., Viitanen M. and Keto P., 2008b. Tests to Determine Water Uptake Behaviour of Tunnel Backfill. SKB Report R-08-134	Relevant parts	
Dixon D., Sandén T., Jonsson E. and Hansen, J., 2011. Backfill of Deposition Tunnels: Use of Bentonite Pellets. SKB Report P-11-44	Relevant parts	
Dixon D., Jonsson E., Hansen J., Hedin, M. and	Relevant parts	

Ramqvist, G., 2011. Effect of Localized Water Uptake on Backfill Hydration and Water Movement in a Backfilled Tunnel: Half-Scale Tests at Äspö Bentonite Laboratory. SKB Report R-11-27	
Gunnarsson D., Börgesson L., Hökmark H., Johannesson L.-E. and Sandén, T., 2001. Äspö Hard Rock Laboratory: Report on the Installation of the Backfill and Plug Test, SKB Report IPR-01-17	Relevant parts
Gunnarsson D., Morén L., Sellin P. and Keto P., 2006. Deep Repository – Engineered Barrier Systems. Assessment of Backfill Materials and Methods for Deposition Tunnels. SKB Report R-06-71	Relevant parts
Johannesson L-E. and Nilsson U., 2006. Deep repository – Engineered Barrier Systems. Geotechnical Behaviour of Candidate Backfill Materials. Laboratory Tests and Calculations for Determining Performance of the Backfill, SKB Report R-06-73	Relevant parts
Johannesson L-E., Sandén T., Dueck A. and Ohlsson L., 2010. Characterization of a Backfill Candidate Material, IBECO-RWC-BF. Baclo Project – Phase 3, SKB Report R-10-44	Relevant parts

Keto P., Dixon D., Jonsson E., Börgesson L., Hansen J. and Gunnarsson D., 2009. Assessment of Backfill Design for KBS-3V Repository, SKB Report R-09-52	Relevant parts
Sandén T., Börgesson L., Dueck A., Goudrazi R. and Lönnqvist M., 2008. Deep Repository – Engineered Barrier System. Piping and Erosion in Tunnel Backfill. SKB Report R-06-72	Relevant parts
Wimelius H. and Pusch R., 2008. Backfilling of KBS-3V Deposition Tunnels – Possibilities and Limitations, SKB Report R-08-59	All

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The Authority reports to the Ministry of the Environment and has around 315 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

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