Strål
säkerhets
myndigheten

Swedish Radiation Safety Authority

Authors: David Bennett

Research

2010:38

The feasibility of Backfilling a Repository of Spent Fuel: An Assessment of Recent Developments by SKB

Report number: 2010:38 ISSN: 2000-0456
Available at www.stralsakerhetsmyndigheten.se

Title: The feasibility of Backfilling a Repository of Spent Fuel: An Assessment of Recent Developments by SKB
Report number: 2010:38
Author: : David Bennett
TerraSalus Limited, Orchard House, Church Lane, Bisbrooke, Oakham, Rutland, LE15 9EL, UK
Date: December 2010

This report concerns a study which has been conducted for the Swedish Radiation Safety Authority, SSM. The conclusions and viewpoints presented in the report are those of the author/authors and do not necessarily coincide with those of the SSM.

SSM Perspective

In the Review Statement and Evaluation of SKB's RD & D programme 2007 (SKI Report 2008:48E), the former Swedish Nuclear Power Inspectorate (SKI) commented that considerable work remained to be done for knowledge of both practical management issues on backfilling and analysis of long-term backfill evolution to reach the same level as for the canister and the buffer. SKI considered that the backfill material had not been thoroughly reported in the RD & D programme. More concrete plans were also needed relating to large-scale demonstration experiments to investigate the performance of the backfill in as realistic conditions as possible.

In the spring of 2009, noting that SKB had changed its concept for backfilling several times over the last few years, and after having visited SKB's most recent backfilling trials at Äspö, both SSM and SSM's expert group BRITE had strong concerns regarding SKB's programme for backfilling the repository tunnels.

Although the BRITE expert group has been keeping a watching brief over SKB's development work on backfilling, SSM has not undertaken a systematic assessment of SKB's work in this area since the SR-Can Safety Report was reviewed in 2006. Dr David Bennett, a member and secretary of the BRITE expert group, was asked to do such an assessment. This report describes the assessment results.

Background

The KBS-3 concept for final disposal of spent nuclear fuel developed by SKB relies heavily on a system of engineered barriers, including an engineered backfill, to isolate and contain the waste.
According to the concept, tunnels leading to the waste deposition holes and other excavations will be backfilled. SKB's current plan is to develop a backfill based on bentonite clay blocks and pellets.

Objectives of the project

The objectives of this report are to document a systematic high-level assessment of information published by SKB on backfilling in the period between late-2006 and 2010. The results from the report are intended to inform SSM concerning the status of SKB's work.

Results

SKB has described its philosophy and concept for backfilling. The concept has evolved from one based on in-situ compaction of granular backfill materials in disposal facility tunnels, to a concept that involves the emplacement of pre-compacted clay blocks surrounded by bentonite pellets. SKB has undertaken various laboratory experiments on potential backfill materials and has conducted some half-scale trials to test the practicalities of backfill emplacement.

Key issues that may affect the performance of the backfill and the feasibility of backfilling operations are described. Issues that could benefit from additional research and development are identified.

At this stage the backfill materials and methods to be used have not been selected and, according to SKB's reports, decisions on these aspects may not be made until well after the forthcoming Licence Application in 2011. This means that SSM may need to consider several alternative backfills and backfilling methods in its review and assessments. SKB's reports suggest that at least another ten years of work will be needed to adequately develop and test its plans for tunnel backfilling.

Project information

Project management: Jinsong Liu
Project reference: SSM 2010/1252

Contents

1. Introduction **2**

2. Objectives and Scope **3**

3. Approach **4**

4. SKB Publications on Backfill Late-2006 to 2010 .... **6**

4.1 Assessment of backfill materials and methods for deposition tunnels, SKB R-06-71 6
4.2 Geotechnical behaviour of candidate backfill materials, SKB R-06-73 9
4.3 Piping and erosion in tunnel backfill, SKB R-06-72 10
4.4 Backfilling of KBS-3V deposition tunnels - possibilities and limitations, SKB R-08-59 13
4.5 Backfilling and closure of the deep repository - pilot tests to verify engineering feasibility, SKB R-08-131 18
4.6 Tests to determine water uptake behaviour of tunnel backfill, SKB R-08-134 20
4.7 Half-scale tests to examine water uptake by bentonite pellets in a block-pellet backfill system, SKB R-08-132 22
4.8 Erosion and sealing processes in tunnel backfill materials, SKB R-08-135 24
4.9 Wetting and homogenisation processes in backfill materials, SKB R-08-136 27
4.10 Mechanical interactions between buffer and backfill, SKB R-09-42 29
4.11 Assessment of backfill design for KBS-3V repository, SKB R-09-52. 29

5. Assessment of Current Status, Issues, Possible Gaps, and Implications **33**

5.1 Assessment of current status on backfilling 33
5.2 The coverage of issues and possible gaps 33
5.3 Relationship to the Licence Application 37

6. Conclusions **38**

7. References **41**

1. Introduction

The Swedish Radiation Safety Authority, SSM, is preparing to make a formal review of a licence application for a geological disposal facility for spent nuclear fuel, which is being prepared by the Swedish Nuclear Fuel and Waste Management Company, SKB. The Licence Application is expected to be submitted in 2011.

SKB refers to its plans for the disposal of spent nuclear fuel as the KBS-3 concept (e.g., SKB TR-06-09). The KBS-3 concept relies heavily on a system of engineered barriers to isolate and contain the wastes.

According to the KBS-3 concept, after 30 to 40 years of interim storage, spent nuclear fuel will be placed in cylindrical copper canisters and these will be disposed of at a depth of about 400 to 500m in crystalline bedrock.

The copper canisters will be placed within a bentonite clay buffer. Tunnels leading to the waste deposition holes and other excavations will then be backfilled and sealed.

Over recent years SSM and its forerunner organisations have established a highly experienced team of technical advisors to support its assessments of SKB's programme. One group of SSM's technical advisors is known as the Barrier Review, Integration, Tracking and Evaluation (BRITE) group.

BRITE has been examining SKB's work on the engineered barrier system and near-field. BRITE's work has involved conducting a series of focused reviews and research projects, and identifying and tracking progress on a set of key issues that will need to be considered in detail during the Licence Application review.

In the spring of 2009, noting that SKB had changed its concept for backfilling several times over that last few years, and having visited SKB's most recent backfilling trials at Äspö, BRITE and SSM expressed concerns over SKB's ability to backfill the repository tunnels.

SSM raised these concerns with SKB at a formal consultation meeting with the municipalities, and again at a later meeting with SKB. In response, SKB provided a list of newly published reports describing its work on the backfill.

SSM, therefore, decided to ask Dr David Bennett of TerraSalus Limited, a member of BRITE, to look more closely at SKB's recent publications on the backfill, and to consider the current status of SKB's work, particularly on the issues of feasibility and implementation.

2. Objectives and Scope

The objectives of this study and report are to undertake and document a systematic high-level assessment of information published by SKB on backfilling in the period between late-2006 and 2010.

The results from the project are intended to inform SSM concerning the status of SKB's work and, thereby, assist SSM's considerations of the level of advancement that SKB's backfilling programme should have reached at different stages in the licensing process.

The work has focused primarily on feasibility and implementation issues. Other topics, such as long-term backfill performance are touched on, but a thorough review of these areas would need to await information expected in the Licence Application.

.

3. Approach

As noted above, the work has involved examining SKB's publications and summarising key aspects of SKB's work, particularly with regards to the feasibility and implementation of backfilling.

Given the relatively large amount of new information from SKB on backfilling, the review has been performed using a 'top-down' approach. Rather than looking in great detail at the entire contents of each published SKB report, the main objectives, summaries and conclusions of SKB's reports have been examined and key points identified. More detailed examinations of SKB's reports have been made as appropriate.

At the start of the project a list of questions regarding what might be expected was developed (see Figure 3_1). This list has been used to help in making an assessment of the current status of SKB's work. The questions were developed as a possible tool for aiding a final evaluation of the degree of confidence in:

- The backfill concept and design.
- The feasibility of backfilling.
- The performance of the backfill.

This pre-licensing project has not covered all of the areas identified in Figure 3_1 and has not attempted to come to a final assessment of confidence in SKB's plans for the backfill, as this would need to await information expected in the Licence Application.

The results from the project are, however, intended to inform SSM concerning the status of SKB's work and thereby assist SSMs consideration of the level of advancement that SKB's backfilling programme should have reached at different stages in the licensing process.

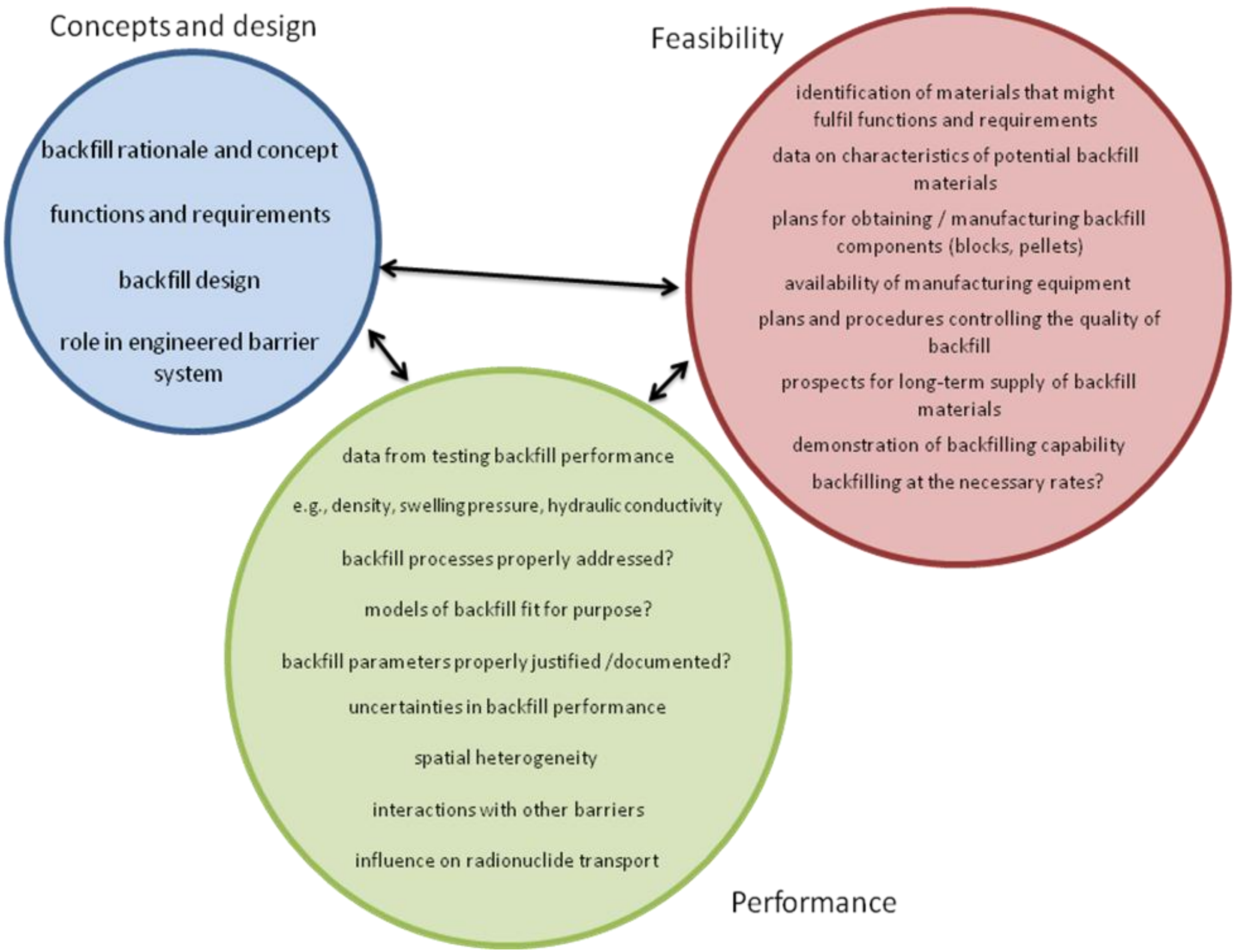


Figure 3_1. Areas of backfill assessment.

4. SKB Publications on Backfill Late-2006 to 2010

This section summarises information published by SKB on backfilling between late-2006 and 2010. BRITE and the Swedish Authorities (SKI and SSI) reviewed earlier information during their consideration of SKB's SR-Can Safety Report (TR-06-09) - see SKI report 2008:23.

4.1 Assessment of backfill materials and methods for deposition tunnels, SKB R-06-71

SKB R-06-71 describes the main function of the deposition tunnel backfill as being to '*sustain the multiple barrier principle by maintaining the safety functions of the individual barriers'*. To maintain this function, '*the backfill in deposition tunnels shall:*

- *Restrict advective transport.*
- *Restrict upwards swelling/expansion of the buffer.*
- *Not in other ways significantly impair the safety functions of the barriers.*
- *Be long-term durable and its functions be preserved in the environment expected in the repository'*.

SKB R-06-71 considers two backfilling methods; (a) compaction of backfill materials *in situ* in tunnels (Figure 4_1), and (b) placement of pre-compacted clay backfill blocks and pellets (Figure 4_2). SKB R-06-71 describes three categories of potential backfill materials:

- **Bentonite clays**: two 'high-grade' Na-bentonites from Wyoming, U.S. (MX-80 and SPV200), one 'low-grade' bentonite from Kutch, India (Asha 230), and one high-grade and one low-grade Ca-bentonite from Milos, Greece (Deponite CAN and Milos clay).
- **Smectite-rich mixed-layer clays**: one from Dnešice-Plzensko Jih (DPJ) in the Czech Republic and one from northern Germany (Friedland clay).
- **Mixtures of bentonite and ballast**: Mixtures consisting of high-grade bentonite (30, 40 and 50 wt%) and crushed rock or sand.

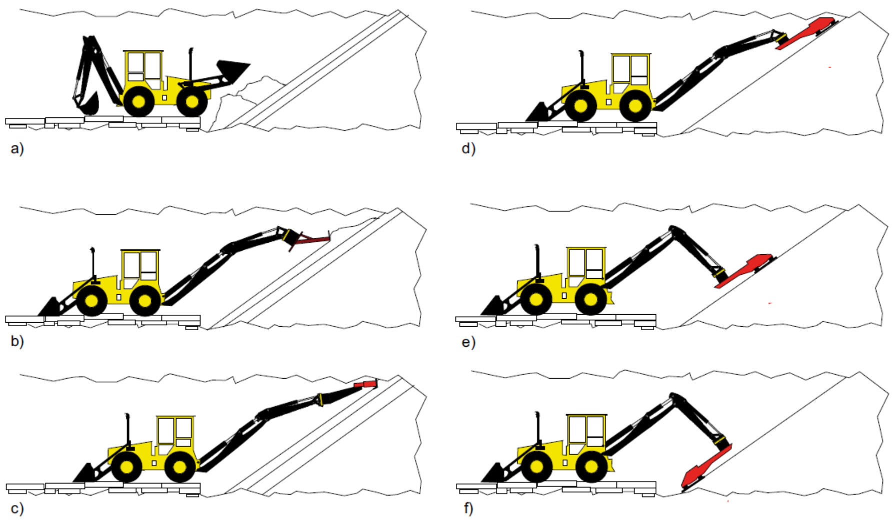


Figure 4_1. **Cartoon illustrating compaction of inclined layers of backfill material in a tunnel (SKB R-06-71).**

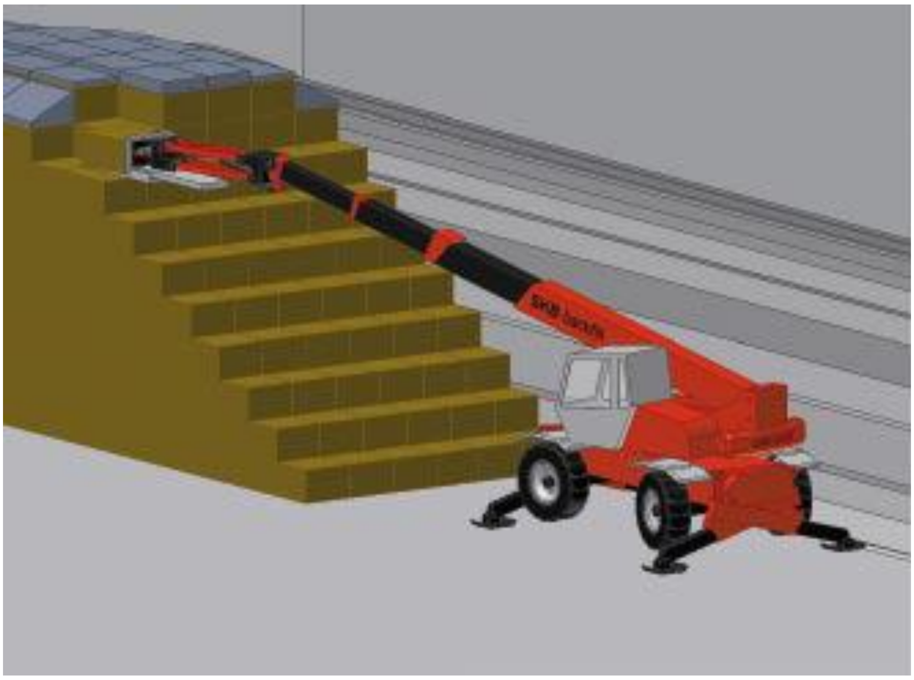


Figure 4_2. **Cartoon illustrating emplacement of pre-compacted clay blocks in a tunnel (SKB R-06-71). In this concept spaces between the backfill blocks and the tunnel walls would be filled with bentonite pellets.**

SKB R-06-71 goes on to:

- Present backfill density criteria relevant to deposition tunnels for the range of potential backfill materials considered.

- Evaluate what densities can be achieved using suggested backfilling methods.

- Compare the density criteria to achievable densities.

- Evaluate 'safety margins' for the combinations of backfill materials and methods considered.

The results of these assessments are expressed in terms of the dry densities that would be necessary at the time of backfill emplacement for the different potential backfill materials to fulfil the long-term density criteria (Table 4_1). The results presented in Table 4_1 were derived assuming that the backfill materials formed a fully saturated barrier with spatially homogeneous properties.

Table 4_1. Dry densities that would be necessary at the time of backfill emplacement for various potential backfill materials to fulfil the long-term density criteria (SKB R-06-71).

Material	Density criterion (kg/m³)	Block concept 80% Filling degree, dry density		In situ concept Achievable dry density from Proctor max: 85% (clays and 50/50) or 90% (30/70)	
		Density (kg/m³)	Margin (kg/m³)	Density (kg/m³)	Margin (kg/m³)
Asha 230	1,160	1,590	430		–
Milos B	1,240	1,640	400		–
DJP	1,400	1,690	290		–
Friedland	1,510	1,820	310	1,470	–40
30/70 bentonite/crushed rock (based on interpolated values)*	1,740–1,890	1,910–1,930	80–170	1,780–1,790	–60–+40
50/50 bentonite/crushed rock	1,560	1,780	220	1,540	–20

Key points and recommendations for further work include:

- SKB R-06-71 notes that backfill density may reduce over time as a result of mass loss by erosion. The report introduces the idea of the need for a 'safety margin' (e.g., in terms of specifying a higher backfill density than would otherwise be necessary) to take account of the potential effects of backfill erosion.

- Backfilling with pre-compacted block and pellets appears to provide higher safety margins than *in-situ* backfilling methods.

- SKB R-06-71 recommends that continued work should focus on the development and testing of the block placing method using three different backfill materials, Friedland Clay, Asha 230 and mixtures of bentonite with different contents of swelling minerals and crushed rock.

- SKB R-06-71 notes that further work should continue on understanding the effect of water inflow during backfill installation and the processes during saturation and homogenisation of the backfill.

- SKB R-06-71 also notes that further work is needed to investigate and assess the technical feasibility of installing the pre-compacted blocks and pellets.

4.2 Geotechnical behaviour of candidate backfill materials, SKB R-06-73

SKB R-06-73 presents results from a relatively small number of laboratory investigations of various clays (Asha 230, Milos, DJP, Friedland, MX-80, SPV200 and Deponit CA-N) and mixtures of clay with 'ballast' (sand, crushed rock, or crushed rock mixed with soil). The experiments were conducted using distilled water, and waters with 3.5% and 7% salinities.

The objective of the investigations was to determine the dry densities of these potential backfill materials that would be required for them to fulfil various requirements in a disposal facility including:

- A backfill swelling pressure of at least 200 kPa.

- A backfill hydraulic conductivity lower than $1{\cdot}10^{-10}$ m/s.

- The ability to withstand compression caused by upwards swelling of the bentonite clay buffer, such that the buffer density at the top of the deposition hole remains greater than 1,950 kg/m^3.

These requirements were based on the safety function indicators used in SR-Can (SKB TR-06-09), although for this study the swelling pressure requirement was raised to 200 kPa from 100 kPa. As in SKB R-06-71, it was assumed that the backfill materials formed a fully saturated barrier with spatially homogeneous properties.

The results showed that, with one exception, the requirement that places the most stringent constraint on backfill dry density is the need to withstand compression caused by upward swelling of the bentonite buffer. This result was conditional on an assumption of compression occurring when both the buffer and backfill were fully saturated. The exception was the 30/70 mixture of bentonite to ballast, for which the hydraulic conductivity and swelling pressure requirements were more important.

The authors of the study noted various limitations, including the small number of tests performed, and the possibility of insufficient homogeneity of the backfill material caused by poor mixing technique.

Piping (the formation of conductive channels due to the action of hydraulic pressure gradients) was observed in some of the clay-ballast mixtures, and the authors suggested that piping and its possible effects on hydraulic conductivity should be investigated further.

4.3 Piping and erosion in tunnel backfill, SKB R-06-72

SKB R-06-72 addressed piping and erosion processes in three potential backfilling materials; a 30/70 mixture of bentonite and ballast, MX-80 pellets, and compacted blocks of bentonite. A first test was also made of the potential for piping channels in a bentonite/ballast mixture to re-heal.

As noted above, piping may be thought of as the formation of conductive channels in bentonite-based engineered barriers due to the action of hydraulic pressure gradients. Piping may lead to erosion.

In the context of this report, the process of bentonite erosion may be thought of as the removal of bentonite from an engineered barrier in groundwater. Bentonite may be eroded in the form of colloids or larger particles. Bentonite erosion may be caused by various physical and chemical processes (SSM report 2010:31; SKB TR-09-35). For example, bentonite may be eroded as a result of chemical processes that lead to bentonite swelling and the formation and dispersion of colloids at the bentonite-water interface, or as a result of shearing by flowing water (if flows are fast enough). Bentonite erosion is dependent on the composition of the clay and the salinity and composition of the aqueous phase.

Several tests were performed to examine the erosion of pre-compacted blocks of bentonite. The experimental set-up is illustrated in Figure 4_3. The tests involved blocks of Friedland clay over which waters were passed at four water flow rates; 0.001, 0.01, 0.1 and 1 l/min. Three water types were used: tap water, and waters with 1% salinity and 3.5% salinity. Sample results from these tests are shown in Figure 4_4.

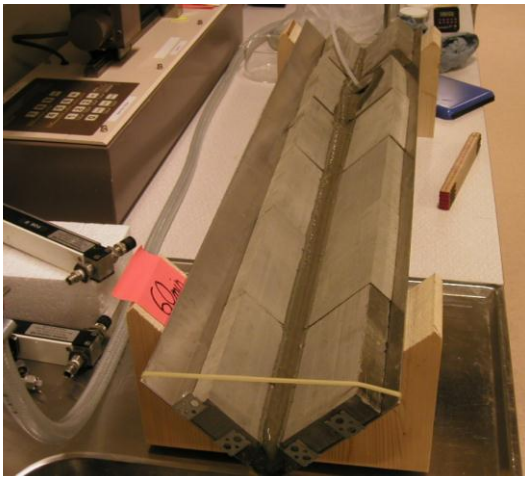


Figure 4_3. Experimental set up used in a series of tests to investigate the erosion of pre-compacted blocks of Friedland clay (SKB R-06-72).

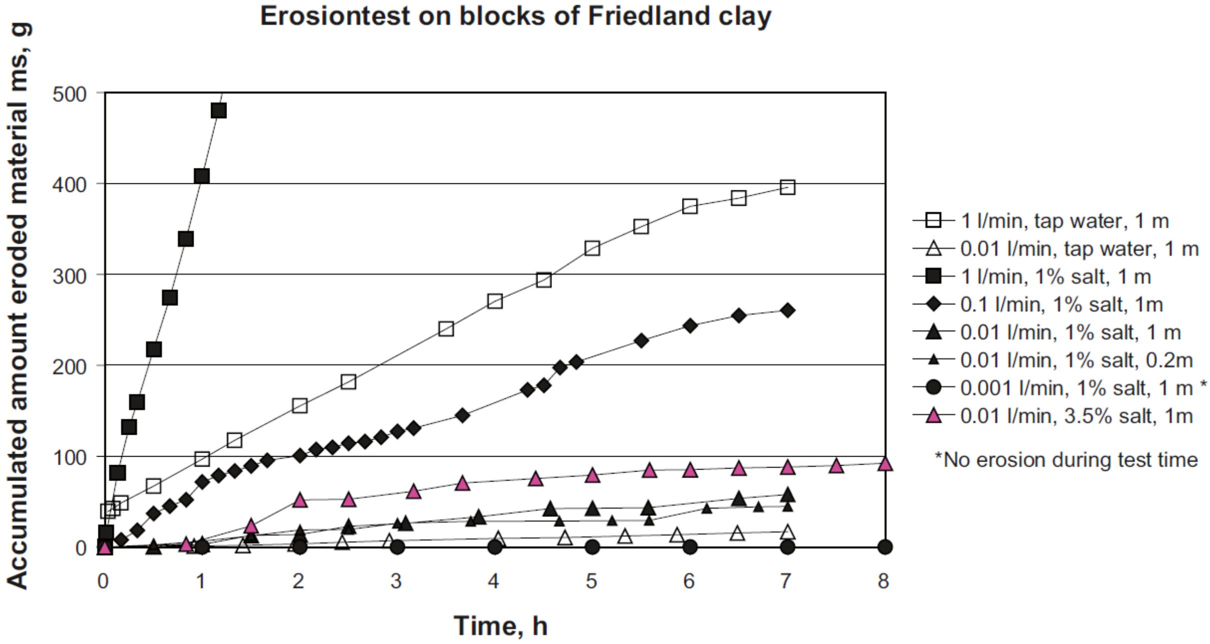


Figure 4_4. Results from tests to investigate the erosion of pre-compacted blocks of Friedland clay (SKB R-06-72).

The results from these tests illustrate that pre-compacted block formed from clay backfill materials are susceptible to erosion by flowing water. The erosion rate is strongly positively correlated to the water flow rate. The salinity of the water also has a strong influence on the erosion rate.

SKB R-06-72 also reports tests that involved placing MX-80 pellets in tubes and in artificial slots, and similar tests with tubes involving 30/70 mixtures of bentonite and crushed rock (Figures 4_5 and 4_6). These tests were designed to study the behaviour of bentonite backfill materials when exposed to different water flow rates and water salinities. One experiment was also conducted with the aim of examining the ability of a bentonite-crushed rock mixture to heal itself after piping had occurred.

Piping and strongly channelled flow was observed in six of the eight tests that involved placing MX-80 pellets in the Plexiglass tubes. In the other two of these tests, the swelling of the bentonite was sufficiently fast to seal off any flow paths and prevent piping. These latter tests involved the lowest water flow rates (0.001 l/min) and a test with a low flow rate (0.01 l/min) and salty water (3.5%).

In the strict sense piping was not observed in the tests with 30/70 mixture of bentonite and crushed rock, but in one case channelled flow occurred where the bentonite had been partially eroded out of the tube leaving behind flow paths containing only crushed rock (Figure 4_7). SKB R-06-72 reports that the ability of the bentonite-ballast mixture to heal such channels by swelling of the remaining clay was very low.

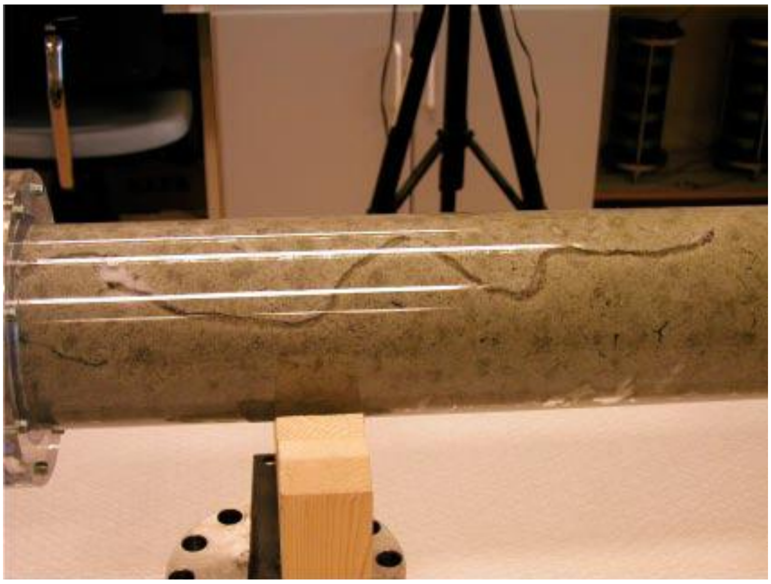


Figure 4_5. **Photograph of a channel formed by piping during a test in which a 1% salt solution was passed at a flow rate of 0.1 l/min through bentonite pellets in a Plexiglas tube (SKB R-06-72).**

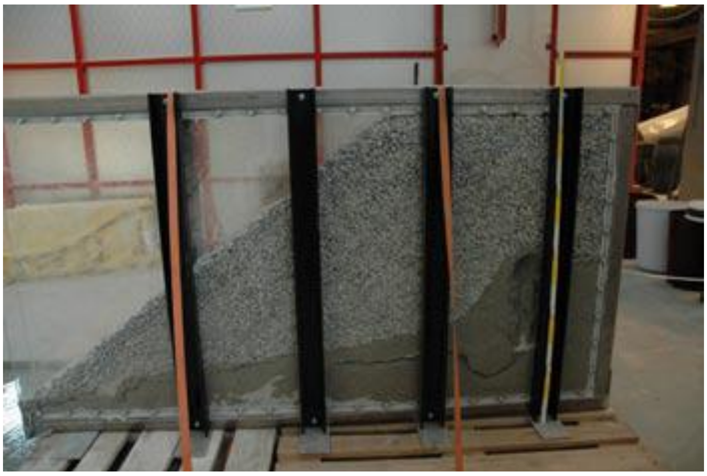


Figure 4_6. **Photograph of bentonite pellets placed in an artificial Plexiglas fracture being filled with water. Note the localisation of wetting and the formation of a channel by piping (SKB R-06-72).**

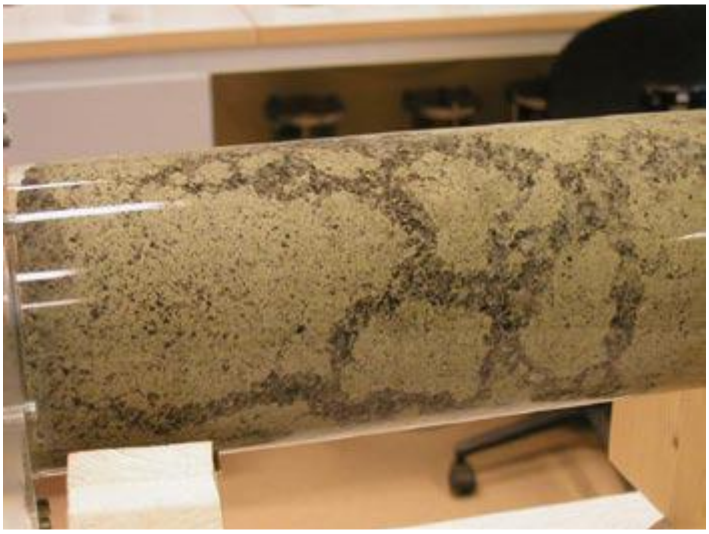


Figure 4_7. Photograph of channelled water flow through a mixture of MX-80 bentonite and crushed rock in a Plexiglas tube (SKB R-06-72). In the channels the bentonite was washed out leaving behind the crushed rock.

4.4 Backfilling of KBS-3V deposition tunnels - possibilities and limitations, SKB R-08-59

SKB R-08-59 summarises results from backfilling trials in the Äspö HRL (Hard Rock Laboratory), as well as various laboratory experiments, and explains a decision by SKB to select a backfilling concept in which the major part of the backfill consists of stacked blocks of pre-compacted clay surrounded by clay pellets.

Briefly, using the concept based on *in situ* compaction of backfill materials within the disposal facility tunnels it had proved difficult to achieve high enough backfill densities and low enough hydraulic conductivities with Friedland clay. Friedland clay was favoured by SKB for use as a backfill material because it was less expensive than MX-80 bentonite and showed good resistance to the effects of water salinity.

SKB R-08-59 describes the sequence of activities that would occur in the disposal facility during waste deposition and backfilling, and considers three different options for the emplacement of the backfill blocks.

The design considered in SKB R-08-59 is shown in Figure 4_8. Notably the design includes a sloping ramp feature at the top of the waste deposition hole that will have to be backfilled, and which represents a significant complexity over previous conceptual designs that have been presented.

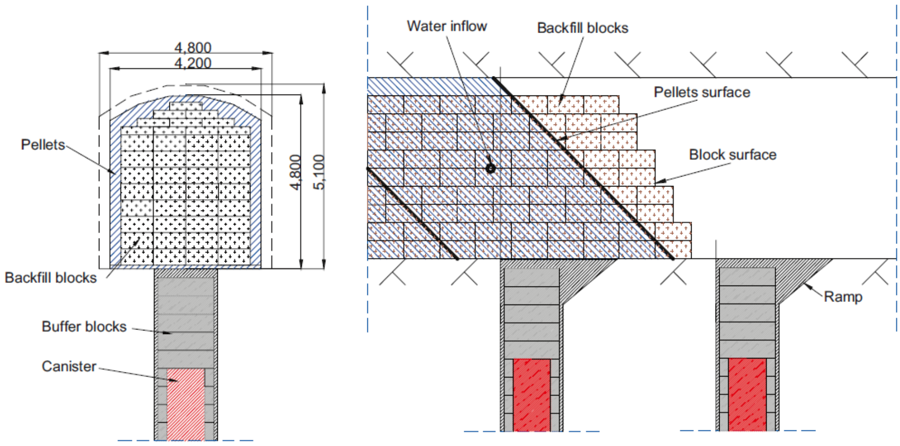


Figure 4_8. Schematic picture of the backfill system tested at Äspö. Left: Cross section of the deposition tunnel with smectite-rich clay pellets surrounding blocks of Friedland clay. Right: Longitudinal section showing sloping pellet fill on both sides of the blocks (SKB R-08-59).

The deposition and backfilling sequence involves:

1) Placing a low-pH concrete foundation at the bottom of the deposition hole and covering this with a copper plate.

2) Use of a buffer protection sheet to protect the buffer rings from moisture and water flowing inwards from the host rock (Figure 4_9).

Figure 4_9. Rubber sheet for protecting buffer blocks from water inflows (SKB R-08-59).

3) Placement of the lower buffer components in the deposition holes.

4) Placement of the waste canister into the buffer.

5) Placement of the upper buffer blocks.

6) Removal of the buffer protection sheet.

7) Filling gaps between the buffer and the surrounding rock with bentonite pellets.

8) Backfilling of the ramp using bentonite granulates and possibly pre-compacted clay backfill blocks.

9) Construction of a 'foundation bed' on the floor of the deposition tunnel using bentonite granulates or pellets, in order to provide a level surface with sufficient strength on which to stack the backfill blocks (Figure 4_10).

Figure 4_10. Preparation of the backfill foundation bed using Minelco granulate (SKB R-08-59).

10) Placement of the backfill blocks in the central area of the tunnel. SKB R-08-59 describes three potential methods for placing of the backfill blocks; the 'Block method', the 'Robot method', and the 'Module method' (see below).

11) Filling gaps between the backfill blocks and the surrounding rock with bentonite pellets.

SKB R-08-59 highlights several potential issues associated with the feasibility of the backfilling process, including:

- **Backfill material storage.** SKB R-08-59 identifies needs for backfilling at a rate of ~800 blocks (6 to 8 m of tunnel) per day, and notes that sufficient storage will be required for at least 2 days worth of blocks. Whilst in storage and transport, the backfill materials will need to be protected from water (e.g., drips) and from extremes of dryness and humidity.

- **Buffer protection sheet**. SKB R-08-59 notes that '*Removal of the buffer protection sheet (rubber) and filling the space between blocks and rock in the deposition holes with pellets prior to backfilling is a difficult process. It may, in fact, jeopardize the entire backfilling operation should complications associated with its removal develop'*.

- **Ramps**. SKB R-08-59 notes that *'The ramps complicate and increase the risk of delaying the backfilling operation'.*

- **Piping and erosion**. SKB R-08-59 notes that *'Water flowing into backfilled parts of the deposition tunnels may cause piping and erosion that can jeopardize the backfilling operation by softening the latest applied clay materials. This process is particularly important at low backfilling rates, which means that great effort has to be made to perform the individual operations, i.e. completing the deposition holes, placing of blocks, and filling of pellets, without delay.' 'The most important factor for obtaining a satisfactory backfill is the rate of inflowing water.' 'A key problem is that the successively hydrating and tightening backfill that has already been placed causes an increase in water pressure at the contact between rock and backfill, which redirects water to flow towards the less pressurized, outer end of the backfill via the EDZ* [Excavation Disturbed Zone]. *Here, successively more water hence flows from the rock and makes backfilling more difficult by causing softening, piping and erosion.' 'The practical experience of backfilling with respect to the impact of inflowing water is very limited and the transient change in water pressure and lack of information of how the inflow spots are distributed makes it difficult at present to define what the rate of backfilling needs to be in order to avoid unacceptable softening of the backfill, particularly of the pellet fill'.*

- **Parallel working**. SKB R-08-59 notes that the potential for piping and erosion leads to the possible need for backfill related operations to proceed in as many as five separate deposition tunnels at once in order to increase the efficiency of the process and minimise the time during which the backfill materials could be affected by these processes.

- **Backfill block emplacement method.** As noted above, SKB R-08-59 describes three potential methods for placing of the backfill blocks; the Block method, the Robot method, and the Module method. The Block method would involve individual handling and placement of backfill blocks. This is relatively tedious and may cause unacceptable delay in backfilling rate if even minor disturbances occur. 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. 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, 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. At present, however, only blocks of the size required for the Block method and Robot method can be manufactured on an industrial scale. Table 4_2 (from SKB R-09-52) summarises some of the perceived advantages and disadvantages of the three methods.

Table 4_ 2. Comparison of different backfill installation methods (R-09-52).

	Block method	Robot method	Module method
Installation principle	Block by block placement	Block by block placement	Placement of modules with blocks
Block size	667×700×510 mm and 600×700×250 mm	308×500×300 mm	666×1,333×500 mm and 444v222×100 mm
Needed equipment	1. Block placing unit	1. Robot-based block placing equipment (two robots)	1. Block placing equipment (fork truck)
Estimated rate	60 s for placement of one block Possible to backfill 6 m/24 hours	30 s for placement of one block Possible to backfill 6–8 m/24 hours	5 min for placement of one module Possible to backfill up to 10 m/24 hours
Advantages	Shown that 60% block filling degree can be reached and that one block can be placed in 60 s	Quick automatic handling of blocks	Block placing equipment is available with only limited development required
Disadvantages	There are only small margins if problems occurs in the process It has not been shown that blocks of this size can be pressed (the tests were done with concrete blocks)	Not tested in practice	It has not been shown that bottom blocks of this size can be pressed

- **Block filling density.** The deposition tunnels will be created by blasting and will have varying cross sections, because of the orientations of the blasting holes. This means that a varying fraction of blocks to pellets would have to be installed along the tunnel for constant density and hydraulic conductivity values to be achieved. The efficiency of filling will depend on the type of clay used in the blocks. For example, using Friedland clay for block preparation, the filling efficiency must be 80%. The filling efficiency could be reduced to 60% if more smectite-rich clay was used. SKB R-08-59 indicates that use of clay with high smectite content would be superior from emplacement point of view.

- **Pellet emplacement.** SKB R-08-59 suggests that *'The pellet filling, which is common to all the methods, is the least well defined and safe part of the backfilling process. Possible heterogeneities in the fill are hard to identify and may remain undetected'.*

SKB R-08-59 concludes by proposing that the Block method should be identified as the reference method for backfill block emplacement in the forthcoming Licence Application reports, but that investigations of the other two block emplacement methods should also continue. SKB R-08-59 suggests 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 currently less well developed and tested. The implication is that at least another ten years of work will be needed to adequately develop and test plans for tunnel backfilling.

4.5 Backfilling and closure of the deep repository - pilot tests to verify engineering feasibility, SKB R-08-131

SKB R-08-131 describes various laboratory experiments and calculations aimed at assessing processes during installation and saturation of the backfill that may affect the long-term performance of the bentonite buffer and the backfill.

One of the main functions of backfill is to restrict upwards buffer expansion, which could lead to a decrease in the density of the buffer in the deposition hole. The criterion used as a basis for the investigations was that at the level of the canister, the buffer density at saturation should not fall below 1,950 kg/m^3.

The main objective of the work reported in SKB R-08-131 was to study a case where the buffer was assumed to be fully saturated, but the backfill consisting of pre-compacted blocks and pellets were assumed to be unsaturated. By considering this case the work is complimentary to that described in SKB R-06-73 (see Section 4_2 above) in which both the buffer and backfill were assumed to be fully saturated. SKB R-08-131 argues that reality would lie somewhere between these two cases.

Calculations of buffer swelling and backfill deformation were made for different types of potential backfill materials. The compressibilities of the pellet filling and the compacted blocks were studied with laboratory measurements to produce input data for the calculations. The strength of the compacted backfill materials was investigated. The hydraulic conductivity and swelling pressure of the investigated backfill materials were evaluated for the material densities expected in the backfill blocks.

The tests were made with following materials:

- Indian Asha 230 bentonite.

- Friedland clay.

- A 30/70 mixture consisting of Deponit CAN Ca-bentonite and crushed rock.

The samples were prepared with distilled water. More saline waters (3.5% and 7% salinity) were used when investigating hydraulic conductivity and swelling pressure.

Measurements of the compressibility of different type of pellets were also taken. The tests were conducted with the following types of pellets and granules:

- Cebogel bentonite pellets with a montmorillonite content of about 80%.

- Minelco granules consisting of Na-activated Ca-bentonite from Milos, Greece.

- Friedland clay granules with a smectite content of about 45%.

- MX-80 pellets with a smectite content of about 75–80%.

The strengths of the materials were evaluated from unconfined one-dimensional compression tests on samples compacted with 25 MPa compaction pressure. These showed that the Friedland clay samples had the highest unconfined compressive strength of about 5,000 kPa.

The compressibility measured on three different pellet fillings show a variation between the materials. The highest compressibility was measured for Friedland clay granules while Minelco granules were the stiffest material.

Calculations of the compression of unsaturated backfill above the swelling buffer were made based on two alternative assumptions about the backfill. In the first case, the backfill was assumed to be homogeneous and to fill the deposition tunnel above the deposition hole. In the second case, the backfill was modelled as a pile of blocks above the buffer in the deposition hole with no lateral support from the surrounding backfill or host rock. Neither set of calculations took account of the ramp feature shown in Figure 4_8.

The model of the second case resulted in the largest calculated backfill compressions, with displacements of up to about 14 cm. The differences in the calculated displacements between different materials were very small.

SKB R-08-131 notes that for the second case, when the saturation of the backfill is low and the buffer in the deposition hole is saturated, there might be a risk of mechanical failure of the backfill. For a backfill composed of a material with the properties of Asha 230, the safety margin for failure is small (SKB R-08-131).

The hydraulic conductivities and swelling pressures evaluated were much lower than $1 \cdot 10^{-10}$ m/s, and higher than 200 kPa, respectively for all of the three materials investigated. This was valid for both types of water used.

4.6 Tests to determine water uptake behaviour of tunnel backfill, SKB R-08-134

SKB R-08-134 reports on a series of 27 tests performed at the 420 level of the Äspö HRL to examine the influence of natural Äspö fracture zone waters on assemblies of Friedland clay blocks and bentonite pellets/granules.

The tests involved backfilling hemispherical concrete tunnel mock-ups with a combination of pre-compressed Friedland Clay blocks, Minelco granular bentonite and Cebogel pellets. Both the Cebogel pellets and the Minelco granular bentonite come from Milos in Greece. Pellets or granular material were used to provide a floor on which to stack the clay blocks. They were also used, in all but the first two tests, to fill the space between the blocks and the tunnel walls (Figure 4_11).

Figure 4_11. Blocks of compressed Friedland clay stacked inside a concrete tunnel (SKB R-08-134).

Water was supplied at a fixed quantity per minute, simulating seepage provided from a discrete fracture. As resistance to inflow increased, the metering pumps increased the pressure at which they operated in order to continue to supply the same quantity of water per unit time.

SKB R-08-134 shows that it is essential to provide a clay block backfilling system with lateral support and confinement as quickly as possible following block installation. Exposure of the blocks even to low rates of water ingress can result in rapid loss of block cohesion and slumping of the block materials into the spaces between the blocks and the tunnel walls (Figure 4_ 12).

Figure 4_12. The effect of dripping water on unconfined blocks of compressed Friedland clay (SKB R-08-134).

Installation of granular or pelletized bentonite clay between the blocks and the walls resulted in a system that was generally stable and not prone to unacceptable short-term strains as water entered.

Water inflow does not result in uniform wetting of the backfill pellets and granules (Figure 4_13). Instead there is the potential for rapid movement of water from the inflow points to the downstream face of the backfill. Depending on the inflow rate and the flow paths developed, flow can be via discrete flow channels that are essentially non-erosive or through highly erosive flow paths within the clay blocks.

Erosion generally tends to be highest in the period immediately following first water exit from the backfill and then decreases as preferential flow paths develop to channel the water directly through the backfill, bypassing large volumes of unsaturated backfill.

The results of these tests were used to provide guidance on the conduct of some larger tests, which are summarised in the following section.

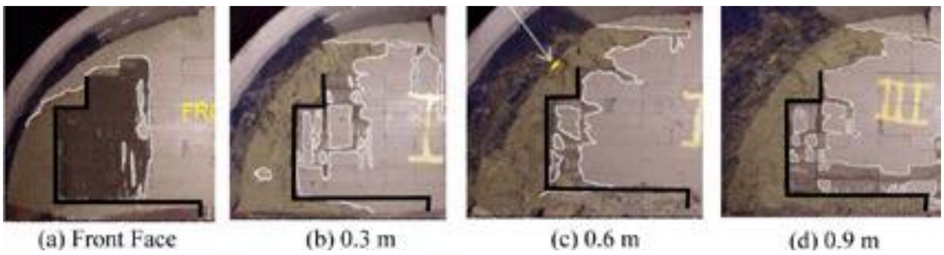


Figure 4_13. Wetting patterns in Test 5 (1.0 l/min for 4.5 hrs). Note the extensive wetting of the pellet fill and the limited wetting of blocks due to rapid inflow and through flow of water (SKB R-08-134).

4.7 Half-scale tests to examine water uptake by bentonite pellets in a block-pellet backfill system, SKB R-08-132

SKB R-08-132 describes a series of 12 tests performed in the surface-based Clay Laboratory at Äspö to examine the effects of water inflow on half-scale assemblies of clay blocks and pellets. The tests described represent a logical development of the smaller scale tests reported in SKB R-08-134 and summarised in Section 4.6 above.

The tests were conducted using half-scale and full-scale mock-ups of repository tunnels, backfilled using a combination of pre-compressed Friedland Clay blocks and Cebogel pellets (Figure 4_14).

Water was supplied to the assembly at rates ranging from 0.1 to 2.5 l/min and the time for water exit, the exit location, the erosion of backfill, the rate of water uptake and resistance of the assembly to water influx were monitored for periods of between 3 and 7 days.

Water was injected at various locations on the outer surface of the backfilled volume to represent the flow of groundwater inwards from the surrounding host rock. In some of the tests a blue dye was used to leave a visible record of the water flow paths.

Various observations were made during the tests, including:

- Significant channelled, rapid flows of water through the backfill material (e.g., Figure 4_15, left). Initial water movement through backfill is largely controlled by the pellets. Water influx of up to 30 l/h at a single location was diverted by the pellets forming essentially horizontal flow channels (pipes) along the chamber wall – pellet interface. These piping features directed the majority of the incoming water around the backfill and towards the unconfined downstream face of the assembly. The time required for the water to exit the assembly was dependent on a combination of inflow rate and distance that it needed to travel.

- Water typically exited the face of the backfill at well-defined locations and once established, these features remained for the duration of the test. The exiting water typically carried only limited eroded material, but could cause some disruption of the downstream face of the backfill as it flowed out of the assembly (e.g., Figure 4_15, right). Longer duration tests (7 days) or those with very long flow paths initially set close to the crown of the chamber show a tendency for the flow to shift to the uppermost regions of the backfilled chamber.

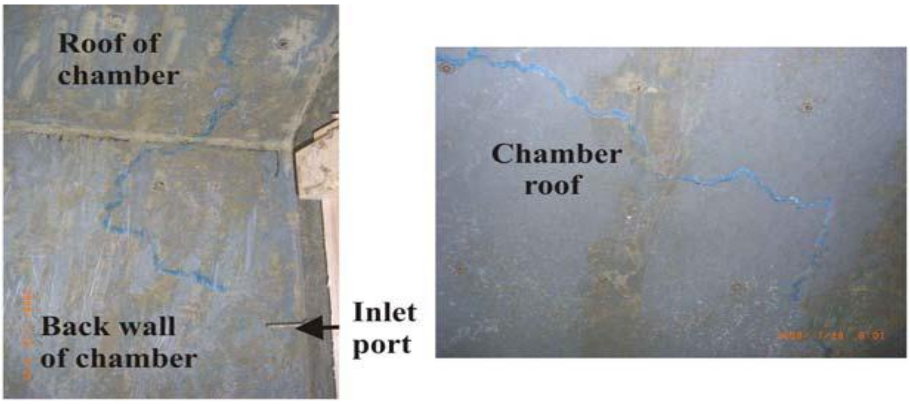
Figure 4_14. Photographs of a half-scale backfill test. Bentonite backfill was emplaced as pre-compacted bentonite blocks inside a half scale tunnel mock up (left). A wooden former (right) was used to reduce the total amount of backfill needed for the test as compared with the repertory situation. Spaces between the tunnel wall and the bentonite blocks were filled with bentonite pellets. Water was injected into the backfill at various rates through holes in the tunnel walls (SKB R-08-132).

Figure 4_15. Photographs of water spraying out from the front surface of the backfill test (left) and the erosion of bentonite pellets (right) illustrating the effect of piping, channelled flow and erosion (SKB R-08-132).

- At point-source inflow rates exceeding approximately 30 l/h the risk of developing undesirable internal flowpaths or erosive flow through the pellet fill increased. At point inflow of 150 l/h, the system experienced extensive and ongoing erosion of the pellet-fill portion of the backfill near the downstream face (Figure 4_15, right). Despite disruption at the front face, the backfill did not undergo substantial internal damage during the 3 days of test operation.

- Where used, the blue dye was seen to arrive at the front surface of the test very quickly after injection, and after partial dismantling the dye provided evidence of channelled flow (Figure 4_16).

According to SKB R-08-132, the measured rate of piping feature advance indicates that in order to backfill at a rate of 8 m/day and avoid water from a previously backfilled volume entering the excavation at substantial rates, the total influx along a single discrete piping feature cannot be more rapid than about 0.5 l/min (30 l/h).



(a) Test 11 showing flow path along back wall and roof of chamber

(b) Test 12 showing flow path along wall of chamber

Figure 4_16. Photographs of the inner surface of the bentonite backfill after partial dismantling of a half-scale tunnel mock up. Blue dye shows evidence of channelled flow (SKB R-08-132).

4.8 Erosion and sealing processes in tunnel backfill materials, SKB R-08-135

SKB R-08-135 describes a wide range of experiments on potential backfill materials. The areas investigated included:

1) **Erosion of pre-compacted blocks.** These investigations involved experiments similar to that shown in Figure 4_3, but with different density clay blocks.

2) **Erosion of MX-80 bentonite pellets.** These investigations involved experiments similar to that shown in Figure 4_5, but with investigation of the effects of fines.

3) **Piping and erosion properties of alternative pellet materials.** These investigations involved experiments similar to that shown in Figure 4_5, but with investigation of MX-80, Cebogel, Minelco and Friedland clays.

4) **Large slot tests.** These investigations involved experiments similar to that shown in Figure 4_6, but with Cebogel pellets.

5) **Displacement of backfill blocks.** The effect of water penetrating into slots between the backfill blocks was investigated using test set ups such as that illustrated in Figure 4_17, left. Two types of tests were performed; in one the displacement was measured and in the other the development of swelling pressure was monitored as physically constrained blocks attempted to separate.

6) **Plug tightness required to stop erosion of backfill materials.** A small number of tests were performed to assess the ability of MX-80 pellets to seal artificial fractures representing spaces between a tunnel plug and the host rock. The ability of MX-80 pellets to seal fractures with apertures of up to 0.3 mm were investigated using waters with salinities up to 3.5 wt %.

7) **Self-healing ability of backfill materials.** These investigations involved experiments similar to the single healing test made on a bentonite-ballast mix described in SKB R-06-72, but using Asha 230 clay, Friedland clay, a 30/70 mixture of Deponit-CAN and ballast, and MX-80 pellets. The test set up used is illustrated in Figure 4_17, right.

8) **Relative humidity induced swelling of backfill blocks**. These investigations involved experiments where small-scale pre-compacted backfill blocks were exposed to a high relative humidity for three months.

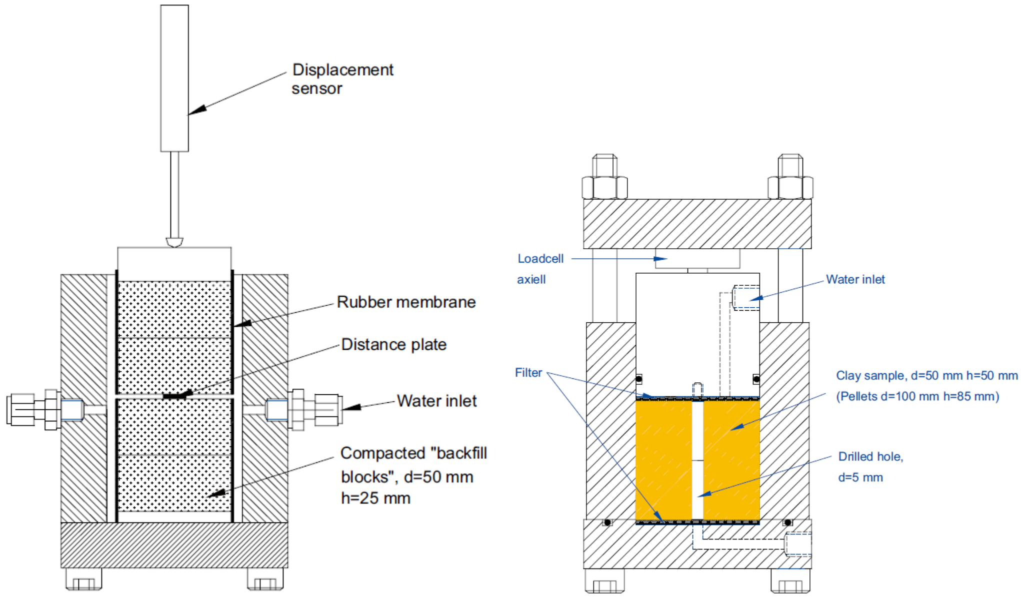


Figure 4_17. Apparatus used to study (i) the displacement of backfill blocks cause by water entering gaps between the blocks (left) and (ii) the ability of various potential backfill materials to seal pre-drilled channels (SKB R-08-135).

Key results from the investigations described in SKB R-08-135 include:

- **Erosion of pre-compacted blocks.** The presence of fines strongly increases the rate of erosion of pre-compacted Friedland clay blocks, but this effect only lasts during the first 24 hours of water flow.

- **Displacement of backfill blocks.** The effect of water entering gaps between emplaced backfill blocks depends strongly on the initial width of the gap. In tests using Friedland clay blocks, water influx to a small initial gap resulted in rather large movements of the blocks, with deformation starting immediately. A large initial gap resulted in smaller overall movement with deformation not starting until about 1.5 to 2 days after test start. Asha 230 blocks behaved in a similar manner to the Friedland blocks, but blocks made of a 30/70 bentonite/ballast mixture showed no movement, which suggests that the bentonite ballast mixture was relatively more permeable.

- **Plug tightness required to stop erosion of backfill materials.** The ability of MX-80 pellets to seal a neighbouring artificial fracture (representing a gap next to a tunnel plug) was tested. The results suggest that for flow rates of 0.01 to 0.1 l/min, and using a 1 wt % salt solution, the maximum fracture aperture that can be sealed is 0.15 mm. SKB R-08-135 notes that the number of such tests performed is limited and suggests that the results obtained should be seen as an indication of the capability for bentonite to seal fractures rather than an absolute measure of their sealing ability.

- **Self-healing ability of backfill materials.** The self healing ability of the candidate backfill materials was studied by drilling holes in saturated samples and then letting them have access to water for three weeks in order to swell and seal the drilled hole. During this three-week period there was no forced flow of water through the artificial piping channels drilled in the samples. Samples made of saturated Friedland and Asha 230 clays exhibited a strong ability to seal the drilled holes. MX-80 pellets installed at a bulk dry density approximating that achievable in a backfilled tunnel showed some tendency to swell and fill the artificial piping channel, but had not healed fully in the three-week period and were unable to withstand renewed water percolation. A 30/70 bentonite/ballast mixture showed no ability to seal the drilled hole. It is noted that these tests were performed under saturated conditions and with no flow, but that in a repository situation, piping is expected to occur before full saturation and flows would be expected during the resaturation process. SKB R-80-135 recommends consideration of the ability of partially saturated backfill materials to seal piping channels.

- **Relative humidity induced swelling of backfill blocks.** The experiments where small-scale pre-compacted backfill blocks were exposed to a high relative humidity for three months showed that compacted blocks are very sensitive to the air humidity and are prone to crack if the relative humidity is not in balance with the suction within the blocks.

4.9 Wetting and homogenisation processes in backfill materials, SKB R-08-136

SKB R-08-136 describes three sets of experiments which were designed to examine:

- Backfill homogenisation during saturation of pre-compacted blocks (of Asha 230B or Friedland clays) when placed next to pellets (of Cebogel, MX-80, Minelco or Friedland clay) and exposed to waters of various salinities.

- Water uptake processes for different clay materials and water types.

- The water retention curve for two potential block materials; Asha 230B and Friedland clays.

Key results from the investigations described in SKB R-08-136 include:

- **Water uptake.** The water uptake tests show that the saturation rate of the backfill is very dependent on the type of material, the initial dry density and the salinity of the water used.

- **Backfill homogenisation**. When different materials are used together for backfilling of a deposition tunnel (e.g., backfill blocks made of one material next to pellets composed of another material), the different retention and mechanical properties of the materials imply that different water contents and densities will be reached at equilibrium (Figure 4_18). During saturation the low density materials (e.g., the pellets) will tend to be compressed by the swelling pressure from denser material (e.g., the backfill or buffer blocks).

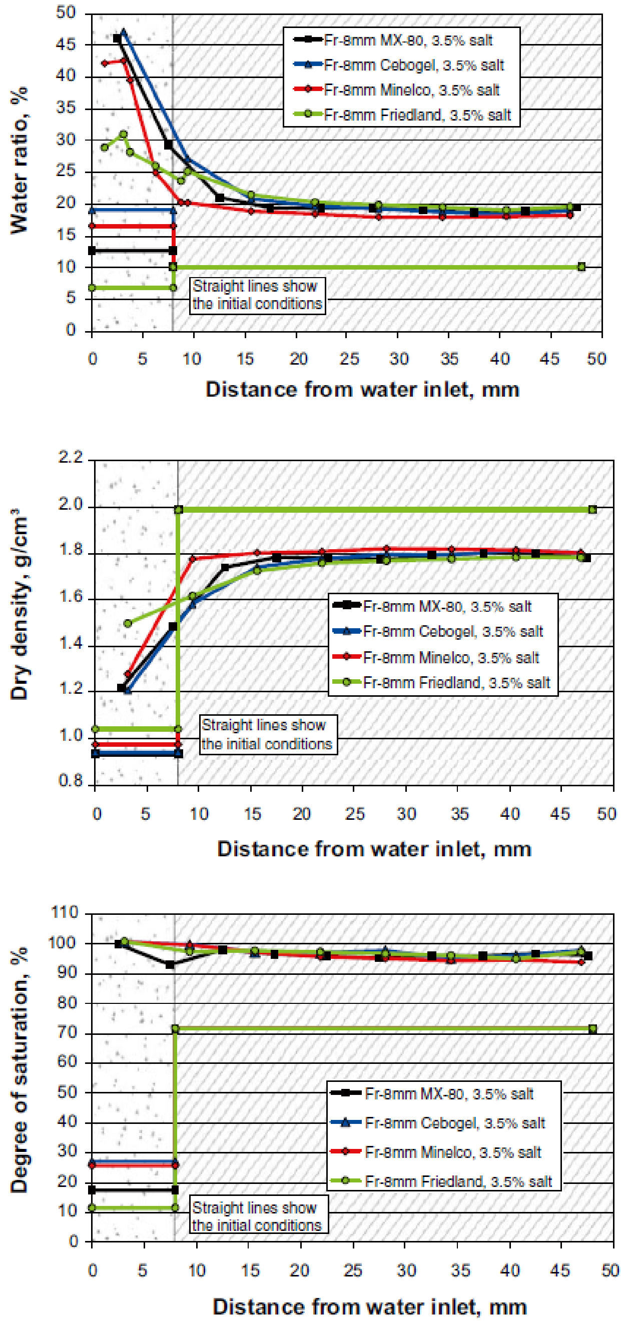


Figure 4_18. **Water content (top), dry density (middle) and degree of saturation (bottom) plotted as function of the distance from water inlet for four specimens of Friedland blocks placed in contact with different pellets (SKB R-08-136).**

4.10 Mechanical interactions between buffer and backfill, SKB R-09-42

SKB R-09-42 describes some three-dimensional (3D), finite element calculations made using the ABAQUS code to assess mechanical interactions between the buffer and backfill during disposal facility re-saturation, clay hydration and swelling.

Two main sets of calculations are described:

- A base case in which both the buffer and backfill materials are saturated. Some sensitivity analyses were run around the base case to begin to assess the effect of materials with different properties.

- An alternative ‘dry’ case in which there is enough water available to saturate the buffer material, but no water at all for wetting of the backfill.

The backfill was modelled as a 3D stack of blocks with additional model elements to represent the gaps initially present between the blocks. It was expected that most of the deformation in the backfill would occur in the joints between the blocks and in the pellets surrounding the sides and the top of the blocks.

SKB R-09-42 notes that the properties of the joints between the backfill blocks are not known, and acknowledges that the model did not include the pellets or granular materials that are expected to be placed on the floor of the deposition tunnels as a foundation bed (see Figure 4_10). It is also noted that the calculations did not take account of the ramp feature at the top of the deposition hole (see Figure 4_8), which has the potential to introduce some complex asymmetry to the problem.

The results from the calculations performed indicate that three key parameters control the interaction between the buffer and backfill, namely the friction angle between the buffer and its surroundings, the stiffness of the backfill and the swelling pressure of the backfill.

The calculated upwards swelling of the buffer varied between 2 and 15 cm for the base case calculations, while it was about 10 cm for the alternative dry case.

SKB R-09-42 notes that further calculations and analysis are needed.

4.11 Assessment of backfill design for KBS-3V repository, SKB R-09-52.

SKB R-09-52 summarises work conducted in the third phase of the Baclo project (including the work summarised in Sections 4_3, to 4_10 of this report and some related studies conducted by Posiva and its contractors), and then goes on to make recommendations concerning backfill material selection, backfill layout, and the effect of key processes on the backfill design.

This section focuses on the information in SKB R-09-52 which goes beyond that summarised in earlier parts of this report, i.e. the discussions, conclusions and recommendations made in SKB R-09-52 concerning the design concept for the backfill, and future research and development.

Key points identified in SKB R-09-52 include:

- In practice a block-filling degree of 60% can be achieved at the specified rate of 6–8 m per 24 hours.

- Some backfill homogenisation tests have been performed for block filling degrees of >70%, but further investigations of the ability of the backfill blocks and pellets to homogenise should be conducted for systems with block filling degrees of less than 70%.

- When contacted with tunnel seepage waters, Friedland clay blocks tended to lose their mechanical stability and are prone to erosion and piping.

- A combination of Asha 230 bentonite blocks (with an estimated smectite content of between 60 and 80%) and bentonite pellets seems to be able fulfil all the requirements set for backfilling at block filling degrees of 70, 80 and 90%. This material also has the potential to fulfil the requirements for backfill at lower block filling degrees (< 70%), but further investigations would need to be made of factors such as homogenisation and compressibility.

- For a Friedland clay backfill (with ~30% swelling clay mineral content), the buffer-backfill interaction requires further evaluation with updated backfill geometry before the material can be judged to be suitable. Based on self-sealing tests, it is recommended that the block filling degree should not be very much less than 70% for this material.

- For a 30% bentonite – 70% ballast mixture, it was determined from theoretical calculations that the block filling degree should be > 80-90%. However, even at this degree of backfilling, the material does not seem to have sufficient self-sealing capacity and is at risk from development of permanent hydraulic piping features.

- Results from field-scale mock-ups undertaken at the Äspö HRL indicate that the backfill will probably be able to tolerate a single-point water inflow of up to 0.5 l/min a few metres behind the backfilling front without significant erosion or mechanical instability being induced in the backfill. However, this requires that the tunnels should be rapidly backfilled for a few metres past any significant inflow point, and that the backfilling process should not be interrupted for more than one week.

- If backfill installation is disrupted due to water inflow, it cannot be ensured that the assumed/required initial state of the backfill will be achieved.

- If the backfilling process is interrupted for more than a week loosening of the materials at the open face of the backfilled volume will almost certainly occur, and such sections would have to be replaced before backfilling operations could restart.

- Further work is needed to select the best method for backfill installation. In addition, there is a need for ongoing re-evaluation of what effects changes in materials, geometries or backfilling approaches will have on the operations of the repository. This is a topic that will require ongoing optimisation as the repository concept moves towards implementation.

- The rate of water inflow into the tunnel can be of critical importance in determining the viability of the block-pellet backfilling concept. Very high point inflow rates can result in substantial localized erosion and weakening of the backfill installed.

- Substantial removal (or internal redistribution) of backfill due to water movement can result in local conditions where the swelling and hydraulic properties of the backfill could drop below the specified limits. This is largely associated with point inflow rate and the degree of saturation that is present within the backfilled volume.

- Water movement through the backfill is likely to develop as discrete flow channels along the rock-pellet interface, resulting in rapid transfer of water from the backfilled tunnel to the downstream face of the backfill. This can have potentially disruptive effects on operations as the water (and eroded clay) must be dealt with such that they do not interfere with ongoing backfilling operations.

Table 4_3, which is reproduced from Table 8-1 in SKB R-09-52, summarises SKB's view of 'critical processes' and technical issues that bear upon the design basis for the tunnel backfill.

Table 4_3. Critical processes and technical issues that bear upon the design basis for the tunnel backfill (SKB R-09-52).

Critical process/ Technical issue	Main activities/output/conclusions from Baclo Phase II and III studies	Input needed in order to resolve question and express it as a design basis
Mechanical interaction between backfill and buffer, i.e. swelling of the buffer to the deposition tunnel	Modelling methods were developed to analyse the process. Taking into account the swelling of the backfill materials, the deformation of backfill seems not to compromise the performance of the buffer (evaluated assuming 78% block filling degree). Following issues were found to affect the mechanical interaction: – Saturation state of the backfill (swelling). – Materials and density state (stiffness) of the materials. – Backfill geometry (block and pellet layout) and block filling degree.	The effect of updated backfill geometry needs to be re-evaluated as well as the influence of materials placed in the upper part of the deposition hole. This may lead to more detailed requirements on thickness of bottom bed and pellet filling at the roof and requirements on block/pellet layout in vicinity of the deposition hole.
Wetting, formation of piping channels and erosion	An extensive amount of information on all three processes was gained in laboratory, ¼ and ½ scale mock-ups. These processes were found to be partly scale and time-dependent. The risk of erosion apparently increases when the single-point inflow is > 0.5 l/min.	Sufficient pellet thickness at the roof/walls has yet to be firmly defined (current estimate ~ 15 cm). The properties of the pellet filling should be optimised considering this issue. The total inflow to a tunnel as well as the maximum point inflow needs to be further investigated and defined. Backfill sequence requires optimisation to improve efficiency. Technical measures to control water inflow need to be developed and tested.
Homogenisation	It was found that sufficient homogenisation was gained with the studied pellet-block combinations for block filling degrees of 70, 80 and 90%.	In practice, the lower the block filling degree, the higher the smectite content of the backfill block should be to provide sufficient swelling and homogenisation. Remains to be studied for lower block filling degrees to study the robustness of the system.
Self-sealing of piping channels	Self-sealing of piping channels was tested for all materials considered for backfilling. Based on the results mixture of bentonite and ballast (30:70) is not recommended as backfill material. In addition, bentonite pellets do not have sufficient self-sealing capacity in their initial dry density after installation (need to be compressed ~ 20% by the blocks).	This process determines material selection for blocks. Sufficient smectite content needs to be defined for density states resulting from block installation efficiencies lower than 70%.
Average dry density/ degree of backfilling	Analysis was made on the achievable average dry densities and the resulting material properties assuming different material alternatives. Tools to design the backfill in terms of material quality and average density have been developed. The achievable block filling degree is affected greatly by the variations in the tunnel geometry and installation method. The current estimation is that 73% of block filling degree can be achieved if the excavation overbreakage is at maximum 20%.	The lower the block filling degree the higher the smectite content of the backfill materials should be.
Installation of backfill components	Installation of backfill blocks and pellets were tested. Sufficient backfilling rate can be achieved with the static installation method under reasonably good conditions.	Static method is recommended if the required backfill rate is high but other options may be suitable under different installation rate requirements. Optimisation of the installation methods for blocks and pellets is still needed and testing under actual repository conditions is required.
Water management	The understanding of the behaviour of wetting, formation of piping channels and erosion comprises a good bases for optimising the backfill design and develop methods for handling water during backfilling.	Development and testing are still needed in order to optimise the backfill design Methods for handling water inflow during backfilling also need to be developed and demonstrated.

5. Assessment of Current Status, Issues, Possible Gaps, and Implications

5.1 Assessment of current status on backfilling

Table 5_1 presents an assessment of the current status of SKB's work on backfilling, based on the set of questions illustrated in Figure 3_1. The method used for undertaking this assessment could form part of SSM's approach to future reviews.

5.2 The coverage of issues and possible gaps

It is clear from the reports examined that SKB has given considerable attention to backfill-related issues over the last few years. This appears to have been a response to an increasing recognition that backfilling of geological disposal facility tunnels to low hydraulic conductivities in fractured rocks is not necessarily straightforward.

SKB's research programme on backfilling has covered a wide range of areas, looking particularly at hydro-mechanical aspects of potential backfill materials, as well as backfilling methods and feasibility. Sensible recommendations regarding the need for further research studies have been made based on the results of individual research projects within the programme. Often it can be seen that recommendations for further study have been taken forward as the programme of studies has progressed. This provides some confidence that a sensible research and development programme is being progressed. It is possible, however, to look across the programme more broadly and identify areas that seem to have received relatively little attention. It is also possible at this time to begin thinking more clearly about site-specific conditions because SKB has selected Forsmark as the potential site for the disposal facility during the period covered by the backfilling research and development work reviewed.

With this context, areas that seem to have received relatively little attention and possible gaps include, in no particular order:

- **Buffer hydration in 'dry' deposition holes.** The host rock at the Forsmark site is believed to be relatively dry. It may be necessary, therefore, to consider the possibility that the backfill may become more hydrated than the buffer in a deposition hole not intersected by significant flowing fractures in the host rock. For such locations buffer saturation may progress mainly from above.

Table 5_1. Assessment of the current status of work in the backfilling area.

Review Questions	Assessment / comments
Backfill Functions and Requirements	
Is the philosophy for backfilling parts of the disposal facility appropriate?	Yes
Has an appropriate description of, and justification for, the functions and requirements of the backfill been provided?	Yes, the latest statement of the functions and requirements of the backfill is given in SKB TR-09-22.
Has the role(s) of the backfill in enabling other components in the natural and engineered barrier system to fulfil their functions and requirements been identified?	The possible interactions between the backfill and the buffer have been identified, but most emphasis seems to have been placed on mechanical effects and less on possible thermo-hydro-chemical aspects.
Feasibility	
Have appropriate materials that could be used to fulfil the functions and requirements of the backfill been identified?	Yes, see Section 4.11 and SKB R-09-52.
Has sufficient data been presented on the characteristics of potential backfill materials (e.g., chemical composition, major and minor phase mineralogy)?	Although some data has been compiled and presented on the geochemical and mineralogical characteristics of potential backfill materials (e.g., Section 5.2 of SKB R-09-52) there is not much information on the variability of the materials.
Have suitable plans for obtaining and manufacturing the components of the backfill (e.g., blocks, pellets) been described? Has sufficient evidence been provided to demonstrate that appropriate manufacturing equipment (e.g., presses) and facilities are available?	The technology for manufacturing standard size backfill blocks and pellets is available, but presses for the manufacture of the larger blocks that would be needed for the Module emplacement method are not currently available.
Has sufficient evidence been presented that there are good prospects for the long-term availability and supply of suitable backfill materials?	No, not in the reports examined here.
Have methods for backfilling the relevant parts of the repository been described, tested and demonstrated?	SKB’s reports address backfilling of straight tunnels, but have not covered any of the more unusual shaped excavations that will occur (e.g., at tunnel junctions or curves). Some testing has been performed, but further testing of backfilling methods will be needed.
Have appropriate plans and procedures for monitoring and controlling the quality of backfill supply, manufacture and emplacement been developed?	No, not in the reports examined here.
Has sufficient evidence been provided to demonstrate that the backfilling methods proposed could be successfully employed at relevant rates within the repository, taking account of the sequencing of operational and waste disposal activities?	SKB argues that a sufficient backfilling rate can be achieved with the static block method under reasonably good conditions (SKB R-09-52), but this may require parallel working in several tunnels at once and needs further testing and demonstration. The methods need to be shown to be capable of coping with non-ideal circumstances and problems that may arise.

Table 5_1. Assessment of the current status of work in the backfilling area (continued).

Performance	
Has sufficient evidence been presented from testing of the performance of the backfill to properly characterise its properties (e.g., density, swelling pressure, hydraulic conductivity) and determine whether the backfill could fulfil its functions and requirements for long-term safety?	A considerable body of information has been gathered and published on the properties of potential backfill materials. However, it would be sensible to conduct a long-term experiment (similar in concept to the Backfill and Plug test) to confirm development within the backfill of the required swelling pressures and long-term hydraulic conductivities.
Does the range of scenarios considered in safety assessment adequately cover the features, events and processes that may occur within, or relate to, the backfill?	Not evaluated in this project.
Has SKB demonstrated that its models of the backfill are fit for purpose, and that the modelling codes have been adequately documented and verified?	Not evaluated in this project.
Has SKB documented data and parameters related to the backfill in a traceable way?	Not evaluated in this project.
Has SKB explained the reasoning, and given appropriate justification, for its selection of backfill parameter values?	Not evaluated in this project.
Has appropriate account been taken of conditions and processes in the repository environment that might affect and cause uncertainties in the properties and performance of the backfill (e.g., changes in temperature, freezing, changes in hydraulic and gas pressures, changes in hydraulic saturation, swelling, piping, erosion, fracturing, chemical reaction and alteration)?	SKB's recent programme on backfilling has taken account of changes in hydraulic pressures, hydraulic saturation, swelling, piping and erosion, but the treatment of these processes in safety assessment has not been evaluated in this project. The reports considered during this project have not addressed changes in temperature, freezing, gas pressures, or chemical reaction and alteration, although it is acknowledged that SKB has addressed these effects to some extent in previous analyses (SKB TR-06-09).
Has appropriate account been taken of the effects of spatial heterogeneity in the properties of the backfill materials and in the conditions in the repository environment that might affect the properties and performance of the backfill (e.g., localised water inflows or erosion)?	SKB is in the process of researching the effects of spatial heterogeneity in the properties of the backfill materials and in the conditions in the repository environment that might affect the properties and performance of the backfill. Localised water inflows and erosion have the potential to be significant and, therefore, work will need to continue, particularly as more becomes known regarding site-specific conditions.
Have sufficient analyses been provided of the interactions between the backfill and other barriers, including consideration of processes that may occur close to the interfaces between the barriers (e.g., thermal spalling; swelling of the buffer; cement-bentonite interactions)?	SKB has provided analyses of some of the possible interactions between the backfill and the buffer, but further analysis seems necessary on spalling, backfill-buffer-interactions and possibly on backfill-cement interactions.
Has appropriate account been taken in safety assessments of the effects and properties of the backfill on radionuclide transport?	Not evaluated in this project.
Do the scenarios, models and parameter values used in the safety assessment adequately represent the uncertainties associated with the backfill?	Not evaluated in this project.

- **Chemical interactions between the backfill, buffer and canister.** Although some data has been compiled and presented on the geochemical and mineralogical characteristics of potential backfill materials (e.g., Section 5.2 of SKB R-09-52) there is not much information on the variability of the potential backfill materials, for example in terms of their contents of accessory minerals and organic matter. The presence of accessory minerals or organic matter might influence chemical conditions within the porewaters of the backfill, act as a source of corrosive species that could migrate towards the canister, and affect radionuclide speciation and solubility.

- **Backfilling of the ramp.** There is a need for clearer plans for, and trials of backfilling the ramp at the top of the deposition hole. Associated with this, there is a need for further hydro-mechanical analysis of buffer backfill interactions that include the ramp.

- **Sealing of piping channels in partially-saturated backfill materials.** SKB has begun to consider the ability of potential backfill materials to seal channels developed during piping but the experiments performed to-date (reported in SKB R-08-135) were done with saturated materials and with no water flow. In the disposal facility piping is most likely to occur in partially-saturated materials. Tests are, therefore, needed to assess the ability of the potential backfill materials to swell and seal piping channels starting from partially-saturated conditions while there is active water flow.

- **Microbial activity in the backfill.** The presence and possible activity of microbes in the backfill and the potential effects of the chemical species they might promote has not been discussed in the reports reviewed. Microbes might live and be active more easily in the backfill than in the buffer because the required swelling pressures are lower.

- **Full-scale backfill trial at realistic rates.** At some point in the programme, it will be necessary to conduct trials to test / demonstrate the feasibility of the reference backfilling method at full scale and at the rates that will be required in the repository. Such trials should include backfill block installation throughout the tunnel section (c.f. the use of wooden formers in the half-scale tests conducted so far – see Section 4.7)

- **Experimental determination of the long-term properties of the backfill.** It would be sensible to conduct a long-term experiment for the block and pellet backfilling concept to confirm development within the backfill of the required swelling pressures and hydraulic conductivities. This test would be similar in concept to the Backfill and Plug test conducted previously.

- **Assessment of the impacts of spatial heterogeneity in the backfill**. SKB's work (e.g., SKB R-08-59) has shown that there are several FEPs (Features, Events, Processes) that have the potential to cause the backfill to have properties (densities, swelling pressures and hydraulic conductivities) that are spatially heterogeneous, both along the tunnels and across the tunnels. FEPs that could result in spatial heterogeneity along the tunnels include the effect of blasting and the amount of rock removed and the rate of water inflow to the tunnels from the rock, which may be focused along a few flow paths. FEPs that will result in heterogeneity of backfill properties across a tunnel include the use of blocks in the centre of the tunnels, pellets near the walls and either pellets or granulates in the foundation bed on the tunnel floors. In addition, piping and erosion of the backfill may be most likely to affect the pellet-filled and granulate-filled regions, where localised reductions in density may result, although they may also affect the backfill blocks in the centre of the tunnels. Together, these points suggest that it would be sensible to consider the need for a performance assessment scenario (possibly a 'what if' scenario) in which the emplaced backfill does not meet or fulfil its requirements, and in which there might be one or more radionuclide transport pathways through the backfilled regions.

5.3 Relationship to the Licence Application

Various aspects of the reports examined, and particularly some statements in SKB R-08-59, suggest that a considerable programme of research and testing work on backfilling will need to be conducted in the period to 2020 and probably beyond.

The backfilling materials and methods to be used are likely to remain uncertain and to an extent be untested at the time of the Licence Application in 2011.

SSM will need to consider carefully, therefore, how it may wish to influence and interact with this programme over the coming years. Options open to SSM include requesting or requiring SKB to undertake particular activities (e.g., backfilling trials and tests) as part of a Performance Confirmation programme, and this might be done through establishing Licence Conditions.

6. Conclusions

An assessment has been conducted of information published by SKB between late-2006 and 2010 on backfilling of a geological disposal facility for spent nuclear fuel.

SKB has given considerable attention to backfill-related issues over the last few years. This appears to have been a response to an increasing recognition that backfilling of geological disposal facility tunnels to low hydraulic conductivities in fractured rocks is not necessarily straightforward.

SKB has described its philosophy and concept for backfilling. The concept has evolved from one based on *in-situ* compaction of granular backfill materials in disposal facility tunnels, to a concept that involves the emplacement of pre-compacted clay blocks surrounded by bentonite pellets. SKB has undertaken various laboratory experiments on potential backfill materials and has conducted some half-scale trials to test the practicalities of backfill emplacement.

SKB's research programme on backfilling has covered a wide range of areas, looking particularly at hydro-mechanical aspects of potential backfill materials, as well as backfilling methods and feasibility. Sensible recommendations regarding the need for further research studies have been made based on the results of individual research projects within SKB's programme. Often it can be seen that recommendations for further study have been taken forward as the programme of studies has progressed. This provides some confidence that a sensible research and development programme is being progressed.

Key issues identified by SKB's programme relating to the feasibility of backfilling operations include:

- The need to protect backfill blocks from water and extremes of humidity and dryness, prior to installation in the tunnels.
- The need for further development and testing of backfill block emplacement methods so that they can deal with non-ideal conditions underground and cope with problems that may arise.
- The potential displacement of backfill blocks by water that enters inter-block gaps.
- The need to develop and test methods for backfilling of the ramps at the top of the deposition holes.
- The potential need for, and logistical implications of, parallel working in several tunnels at one time in order to achieve the required rate of tunnel backfilling.
- Management of water that moves towards the backfilling face through backfill pellets and/or the excavation disturbed zone in order to prevent interruption and delay of backfilling activities.
- Further confirmation of the block filling densities that can be achieved in practice and, based on this, the selection of backfill materials with sufficiently high smectite contents.

Key issues identified by SKB's programme relating to the performance of the backfill include:

- The mechanical behavior of the backfill materials in response to hydration, and interactions between the backfill and the buffer.
- Backfill homogenisation.
- Piping and erosion.
- The ability of backfill materials to seal channels caused by piping.

SKB has considered various clays and other potential backfill materials. Currently SKB appears to be focusing on use of Asha 230 bentonite or Friedland clay for backfill blocks, and MX-80, Cebogel or Minelco pellets. SKB has also described three possible backfilling methods (Block, Robot, Module). Presently all of these materials and methods seem to be under consideration. SKB R-09-52 suggests that the Block method should be adopted as the reference emplacement method, but also implies that later on SKB might wish to move to the Module method, once this has been further developed and tested.

With regard to the choice of backfilling materials, the reports considered tend to suggest (i) that it may be necessary to use one of the higher-smectite clays, and (ii) that mixtures of clay and ballast are unlikely to perform satisfactorily. At this stage, however, the backfill materials and methods to be used have not been selected and, according to SKB's reports, decisions on these aspects may not be made until well after the forthcoming Licence Application in 2011. This means that SSM may need to consider several alternative backfills and backfilling methods in its review and assessments. SKB's reports suggest that at least another ten years of work will be needed to adequately develop and test its plans for tunnel backfilling.

Looking across SKB's programme, it is possible to identify some areas that seem to have received relatively little attention. It is also possible at this time to begin thinking more clearly about site-specific conditions because SKB has selected Forsmark as the potential site for the disposal facility during the period covered by the backfilling research and development work considered. With this context, areas that seem to have received relatively little attention and/or possible gaps include:

- Chemical interactions between the backfill, buffer and canister.
- Buffer hydration in 'dry' deposition holes.
- Backfilling of the ramp.
- Sealing of piping channels in partially-saturated backfill materials.
- Microbial activity in the backfill.
- Full-scale trials of backfilling at realistic rates.
- Experimental determination of the long-term properties of the backfill.
- Assessment of the impacts of spatial heterogeneity in the backfill.

SSM will need to consider carefully how it will interact with SKB's programme over the coming years. Options open to SSM include requesting or requiring SKB to undertake particular activities (e.g., backfilling trials and tests) as part of a Performance Confirmation programme established through appropriate Licence Conditions.

7. References

SKB TR-06-09, SKB, Long-term safety for KBS-3 repositories at Forsmark and Laxemar - a first evaluation. Main report of the SR-Can project, 2006.

SKB R-06-71, Deep repository - engineered barrier system. Assessment of backfill materials and methods for deposition tunnels, David Gunnarsson, Lena Morén, Patrik Sellin, and Paula Keto, 2006.

SKB R-06-72, Deep repository - engineered barrier system. Piping and erosion in tunnel backfill. Laboratory tests to understand processes during early water uptake, Torbjörn Sandén and Lennart Börgesson, 2008.

SKB R-06-73, Deep repository - engineered barrier system. Geotechnical behaviour of candidate backfill materials. Laboratory tests and calculations for determining performance of the backfill, Lars-Erik Johannesson and Ulf Nilsson, 2006

SKB R-08-59, Backfilling of KBS-3V deposition tunnels - possibilities and limitations, Hans Wimelius and Roland Pusch, 2008.

SKB R-08-131, Backfilling and closure of the deep repository. Phase 3 - pilot tests to verify engineering feasibility. Geotechnical investigations made on unsaturated backfill materials, Lars-Erik Johannesson, 2008.

SKB R-08-132, Deep repository - engineered barrier system. Half scale tests to examine water uptake by bentonite pellets in a block-pellet backfill system, David Dixon, Cecilia Lundin, Ellinor Örtendahl, Mikael Hedin and Gunnar Ramqvist, 2008.

SKB R-08-134, Tests to determine water uptake behaviour of tunnel backfill. David Dixon, S. Anttila, M. Viitanen and P. Keto, 2009.

SKB R-08-135, Deep repository - engineered barrier system. Erosion and sealing processes in tunnel backfill materials investigated in laboratory, Torbjörn Sandén, Lennart Börgesson, Ann Dueck, Reza Goudarzi, Margareta Lönnqvist, 2008.

SKB R-08-136, Deep repository - engineered barrier system. Wetting and homogenisation processes in backfill materials. Laboratory tests for evaluating modeling parameters. Lars-Erik Johannesson, Torbjörn Sandén, and Ann Dueck, 2008.

SKB TR-09-22, Design premises for a KBS-3V repository based on results from the safety assessment SR-Can and some subsequent analyses, 2009.

SKB TR-09-35, Mechanisms and models for bentonite erosion, Ivars Neretnieks, Longcheng Liu, and Luis Moreno, 2009.

SKB R-09-42, Mechanical interaction buffer/backfill. Finite element calculations of the upward swelling of the buffer against both dry and saturated backfill. Lennart Börgesson, and Jan Hernelind, 2009.

SKB R-09-52, Assessment of backfill design for KBS-3V repository. Paula Keto, David Dixon, Esther Jonsson, David Gunnarsson, Lennart Börgesson, and Johanna Hansen, 2009.

SKI Report 2008:23, SKI's and SSI's review of SKB's safety report SR-Can, Björn Dverstorp, Bo Strömberg *et al*., 2008.

SSM report 2010:31, Buffer erosion: An overview of concepts and potential safety consequences, Michael J. Apted, Randy Arthur, David Bennett, David Savage, Göran Sällfors and Håkan Wennerström, 2010.

2010:38

The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 270 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.

Strålsäkerhetsmyndigheten
Swedish Radiation Safety Authority

SE-171 16 Stockholm
Solna strandväg 96

Tel: +46 8 799 40 00
Fax: +46 8 799 40 10

E-mail: registrator@ssm.se
Web: stralsakerhetsmyndigheten.se