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System design of backfill

Pellet optimization

Anna Johnsson, ES Konsult AB

Torbjörn Sandén, Clay Technology AB

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Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co

Box 250, SE-101 24 Stockholm
Phone +46 8 459 84 00

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Abstract

Bentonite pellets are planned to be used as part of the deposition tunnel backfill in the KBS-3V repository. Bentonite pellets are used as bed material to even out the blasted tunnel floor before placement of backfill blocks. Pellets are also used to fill the gap between the deposition tunnel walls and the backfill blocks to protect the blocks from direct water flow.

The concept for installation and production of backfill has been further developed during project ÅSKAR – System Design of Backfill. This report summarizes results and main conclusions from the subproject 2; “DP2 Pellet optimization”.

The subproject was initiated with a literature study to compile information on previously performed tests considering use of bentonite-pellet materials as part of buffer or backfill barriers. From this information, potential options and limitations for the use of pellets or pellet-granule mixtures in backfill were identified. Also further investigations and tests to be performed within the subproject were suggested. The literature study is summarized in this report.

Laboratory tests were performed on different backfill pellet candidates in order to optimize the properties regarding water storing capacity and sensitivity to erosion. The work included testing of different pellet materials (ASHA, IBECO, and MX-80) and pellet types (extruded, roller compacted and granules). The general conclusion from the tests was that extruded pellets with a diameter of 6 mm seem to have the best overall characteristics. Regarding materials ASHA and IBECO were superior to MX-80.

Bentonite pellets were produced at different times as part of the subproject. Both extrusion and roller compaction techniques were used. Experiences and problems that occurred during the manufacturing process are presented in the report. Control and adjustment of the water content in the bentonite feeding material was found to be essential to achieve a stable production process.

The final activity within the subproject was a large scale pellet test. Method, results and conclusions from the test is presented in this report. The purpose of the test was to determine the water storing capacity of backfill pellets in full scale. The test was performed in the TASS-tunnel with geometries corresponding to a deposition tunnel. The test result shows that the water storing capacity of the backfill pellet is good. The pellet fill can withstand a few days of interruption in the backfilling process before out flowing water reaches the front face of the backfill stack.

Sammanfattning

Bentonitpelletar är en av komponenterna som ingår i återfyllningen i KBS-3V-förvaret för använt kärnbränsle. Bentonitpelletar har två olika användningsområden i återfyllningen, dels används pelletar som bäddmaterial för att jämna ut det sprängda tunnelgolvet innan installation av återfyllningsblock. Det andra användningsområdet är som fyllning i spalten mellan väggarna på deponeringstunneln och blockstapeln för att skydda återfyllningsblocken från det inflödande vattnet.

Installation och produktion av återfyllningen har vidareutvecklats i projekt ÅSKAR – Systemkonstruktion av återfyllning inom vald referensutformning. Den här rapporten summerar resultat och slutsatser från delprojekt 2, ”DP2 Pelletoptimering”.

Delprojektet inleddes med en litteraturstudie för att sammanfatta information från tidigare utförda undersökningar på återfyllningspelletar och buffertpelletar. Möjligheter och begränsningar för olika typer av återfyllningspelletar och pelletgranulatbladningar identifierades. Baserat på de inledande studierna föreslogs fortsatta utredningar och försök för delprojektet. Litteraturstudien sammanfattas i denna rapport.

För att optimera pelletegenskaperna med avseende på vattenlagringskapacitet och känslighet för erosion genomfördes laboratorietester på olika pellettyper inom delprojektet. Olika pelletmaterial (ASHA, IBECO och MX-80) och pellettyper (extruderade, valskompakterade och granuler) undersöktes. Slutsatsen från laboratorietesterna är att extruderade pelletar med en diameter av 6 mm generellt har de bästa egenskaperna. Gällande material så visade sig ASHA och IBECO ha bättre egenskaper än MX-80.

Bentonitpelletar producerades vid olika tillfällen inom delprojektet. Både extrudering och valskompaktering användes. Erfarenheter och problem som uppkom under tillverkningsprocessen presenteras i rapporten. Styrning och kontroll av vattenkvoten i bentonitmaterialet visade sig vara avgörande för att få en stabil produktionsprocess.

Delprojektet avslutades med ett fullskaligt pelletförsök. Metod, resultat och slutsatser från försöket presenteras i rapporten. Syftet med försöket var att studera de vattenlagrande egenskaperna hos återfyllningspelletar i full skala. Försöket genomfördes i TASS-tunneln som har geometrier som är jämförbara med deponeringstunnlarna. Försöket visar att de vattenlagrande egenskaperna hos pelletfyllningen är goda. Pelletfyllningen klarar några dagars avbrott i återfyllningsprocessen innan utflödande vatten når blockstapelns frontyta.

Contents

1 Introduction

SKB and Posiva are in the process of evaluating options for backfilling in their repository concepts for spent nuclear fuel. Both companies have selected KBS-3V as their reference method for disposal of spent nuclear fuel (SKB 2010a, Posiva 2012). This involves installation of copper canisters in boreholes drilled in the floor of deposition tunnels deep down in the crystalline bedrock, se Figure 1-1. After canister- and buffer installation the deposition tunnels are backfilled. The reference concept for deposition tunnel backfilling involves use of precompacted bentonite blocks to fill the majority of the tunnel volume. Bentonite pellets are used as bed material to even out the blasted tunnel floor before placement of the backfill blocks. Pellets are also used to fill the gap between the deposition tunnel walls and the backfill blocks to protect the blocks from direct water flow.

The reference design for the backfill in SKB's KBS-3V repository is described in SKB (2010b). The concept for installation and production of backfill has been further developed in the project KBP1003 – System Design of Backfill, abbreviated ÅSKAR. The project was initiated to ensure that the reference method for backfilling of deposition tunnels work as intended and meets the requirements regarding quality and verifiability of manufacturing and control.

Within ÅSKAR a subproject called "DP2 Pellet optimization" was initiated to define the optimal backfill pellet properties and look into different pellet manufacturing methods.

This report summarizes the main conclusions and results from the subproject two, DP2 Pellet Optimization. The subproject is a joint project between Posiva and SKB.

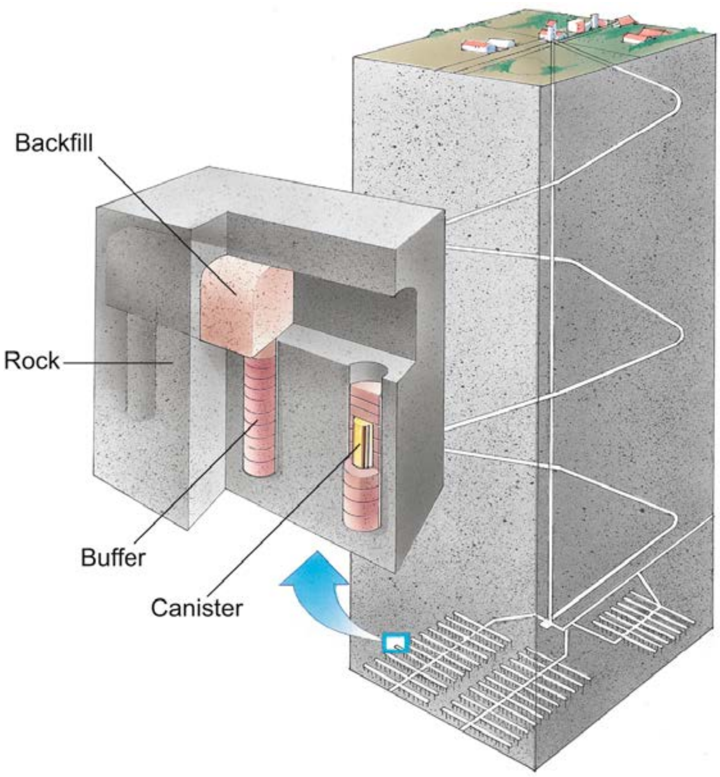

Figure 1-1. *KBS-3 with vertical deposition.*

1.1 Background

Originally, installation of pellets into the gap between the blocks and the surrounding rock mass was not regarded necessary, it was expected that the blocks would swell and fill the limited volume of voids left following block placement. Later it was determined that the backfill does not work reliably without pellets, one risk is that the blocks will be affected by dripping water in the deposition tunnels during installation. Other aspects are that the saturation of the tunnel takes a long time and the density needs to be high enough from the beginning to ensure the fulfilment of performance requirements like compressibility. The pellet filling also help increase the overall backfill density.

Bentonite pellets are also used as bed material to even out the blasted tunnel floor before placement of the backfill blocks. The subproject included testing pellets both for this application and for gap filling.

1.2 Project goals

The main objective of the subproject was to define the optimal pellet properties for backfilling and their manufacturing method. Hence this subproject should

- Identify optimal pellet properties for use as backfill material in the gap between the backfill blocks and the tunnel wall as well as on the tunnel floor.
- Give recommendations for pellet manufacturing and installation.
- In cooperation with subproject DP1 Design define acceptable water inflows and time limits during installation.

The last objective was partly removed from the subproject since a new subproject, DP6 Methods to handle inflowing water, was started to look into different methods for handling water inflow during the installation of backfill. Acceptable water inflows and time limits for the different methods should be defined in DP6. However water inflows and time limits for pellets during installation were studied in laboratory scale and a large scale test in DP2.

2 Pre-assessment

The subproject was started with a literature study presented in Dixon et al. (2011). The objective was to compile information on tests previously performed by various organisations considering use of bentonite-pellet materials as part of buffer or backfill barriers. Experiences related to manufacturing and installation of bentonite-based pellet materials for use in repositories for spent nuclear fuel were reviewed. From this information, potential options and limitations for the use of pellets or pellet-granule mixtures in backfill were identified. Also further investigations and tests to be performed within the subproject were suggested.

Experiences related to pellet material composition, size, shape, placement options and more importantly, the density to which they can be placed all indicate that there are limitations to the achievable as-placed density of bentonite pellet fill. Low as-placed density of the pellet fill component of the backfill is potentially problematic as the outermost regions of tunnel backfill will be the first region of the backfill to come in contact with water entering the tunnels. It is also through this region that initial water movement along the length of the deposition tunnels will occur. This will greatly influence the operations in a tunnel, especially with respect to situations where water is exiting the downstream face of still open deposition tunnels. Pellet-filled regions are also sensitive to groundwater salinity, susceptible to development of piping features and subsequent mechanical erosion by throughflowing water, particularly in the period preceding deposition tunnel closure (Sandén et al 2008, Johannesson et al. 2010).

Field-related factors such as degree of tunnel over-excavation need to be quantified in order to make a more accurate estimation of the quantity of pellet material needed and what the equilibrated density of the tunnel backfill will be.

2.1 Methods to produce bentonite pellets

Pellets can be produced using two basic techniques; firstly by pushing material through a perforated die, see Figure 2-1 (extrusion) and secondly by roller compaction. These two techniques are commonly used in industry to produce compacted pellets of various materials and have been demonstrated to be viable for production of bentonite materials. Granulated bentonite is also discussed as an alternative to pellets in Dixon et al. (2011) but is not regarded as a good alternative due to problems associated with maintaining desired particle size gradation, segregation of material sizes during transport and generation of excessive dust during placement.

Figure 2-1. *Left: pan grinder rolls over die. Right: die with material.*

2.1.1 Extrusion

This technique basically pushes the raw material though a die with the help of pan grinder rolls, which results in a degree of compaction and formation of a cylindrical product, see Figure 2-1 and Figure 2-2. The diameter of these rods can be varied by changing the size of the openings of the die.

The pellets produced by extrusion have limitations regarding the density to which the individual pellet can be produced and can vary considerably in their durability. They have been demonstrated to be durable enough to allow them to be "blown" into place using shotcreting equipment. Extruded pellets have potential for use in backfilling. (Dixon et al. 2011)

2.1.2 Roller compaction

In a roller compactor the bentonite is fed by a screw into a small void above two counter-rotating rolls, each containing matching hemispherical voids. The bentonite is compressed into pellets or briquettes between these rolls and exit by gravity from the bottom of the rollers. A picture of almond shaped roller compacted pellets of ASHA-material is shown in Figure 2-2.

The bentonite pellets produced have been demonstrated to be durable enough to allow them to be poured, augered, blown, or compacted into place and therefore have high potential for use in repository backfilling. (Dixon et al. 2011)

Figure 2-2. *Left: IBECO extruded 6 mm diameter rods. Right: ASHA compacted almond shaped pellets.*

3 Laboratory testing

Testing and evaluation of different backfill pellet candidates was performed in order to optimize the properties regarding water storing capacity and sensitivity for erosion, see Andersson and Sandén (2012). The work included testing of different pellet materials (ASHA, IBECO, and MX-80) and pellet types (extruded, roller compacted and granules).

The performed tests show that the behavior of a pellet filling varies depending on pellet manufacturing method, pellet shape and size as well as the material used. The general conclusion from the tests completed in this study is that extruded pellets with a diameter of 6 mm seem to have the best overall characteristics. Regarding materials ASHA and IBECO were superior MX-80.

3.1 Materials

Four different clay materials were used in the tests:

- **ASHA NW-BFL-L.** The ASHA bentonite material was delivered in November 2010 from Ashapura, India. It is a sodium dominated bentonite with a montmorillonite content of about 70% (Sandén et al. 2013).
- **MX-80.** A high grade sodium bentonite from Wyoming, USA with a montmorillonite content of 80% (Karnland et al. 2006). MX-80 is mainly used as a reference material in the tests.
- **IBECO RWC-BF.** The IBECO material was delivered in February 2011 from Milos, Greece. The material is a natural calcium bentonite with medium montmorillonite content of 64% (Sandén et al. 2013).
- **IBECO HQ (IBECO Deponit CA-N).** An activated high quality bentonite with high montmorillonite content, 75–80%. The material origins from Milos, Greece. The pellets of this material were manufactured by AECL, Canada, and were mainly of interest for Posiva. The pellets made of this material were only tested regarding erosion properties.

3.2 General tests

Dry density, bulk density, water content, compressibility of the pellet filling and strength of the individual pellets were investigated. These general tests aimed at describing the basic properties of the pellet filling candidates.

- The water content of the extruded pellets was higher than in the compacted pellets due to the manufacturing process.
- The bulk density varied in the interval 1,030–1,122 kg/m^3 for the roller compacted pellets and 1,017–1,057 kg/m^3 for the extruded pellets.
- The compressibility was lower for the roller-compacted pellet types, which was expected since they also had a higher dry density and lower water content. Granules was the stiffest material tested and the IBECO extruded 10 mm the softest.

3.3 Erosion

The erosion tests were intended to examine the ability of the various pellet filling candidates to resist the action of flowing water. The evaluation of the results led to the following conclusions:

- In general the extruded pellets were the most resistant to erosion. The compacted pellets seem to be more liable to a direct downward outflow during the initial wetting period, which may also indicate that channels are more likely to be formed.

- When comparing the material types MX-80 seemed to form downward leading flow channels very quickly, allowing the water to move directly out of the fill. ASHA showed some tendencies to seal early, even before the water front reached the outlet in these tests. Both these phenomena are considered negative since the effect is that the pellet filling does not use its entire volume to store water, but the direct outflow is regarded as the worst case. IBECO had the most even wetting behaviour but ASHA seemed to decelerate the water front better.
- No significant influence was observed in any material type from variations in water flow rate.

The main conclusion drawn from the erosion tests is that the extruded IBECO pellets were the most resistant to erosion. However, almost all pellet types were within the limits of a theoretical model describing the erosion rate by Sandén and Börgesson (2010).

3.4 Water storing capacity

The ability of the pellet filling to rapidly take in and hold water originating from the surrounding rock was tested at small scale in a Plexiglas tube and at larger scale in an artificial slot. A summary of the main conclusions from the performed tests is as follows:

- The extruded pellets had a higher flow resistance and seemed to decelerate the water front better than the compacted according to the comparisons in the initial water storing tests.
- Neither ASHA nor IBECO seemed to be much affected by changes in water salinity.
- The initial water storing capacity tests showed that ASHA slowed the advance of the water front better at higher flow rates but IBECO on the other hand seemed to have a more even wetting behaviour at lower flow rates.

3.5 Installation tests

The installation method considered for the pellet fill is to blow the pellets into place with equipment for shotcrete installation. This method was tested on a full scale artificial slot to study to what extent the pellet filling was affected. ASHA 6 mm extruded pellets was found to be the most durable of the pellets examined. The installation method crushed 5.0% of this pellet filling to a size less than 4 mm. IBECO 6- and 10 mm extruded pellets were also quite durable with 7.4% and 7.6% respectively being reduced to < 4 mm. ASHA roller compacted pillows and almonds were the least durable pellet types with a crushing rate of more than 50%.

3.6 Choice of pellet type for full scale test

One of the objectives of the laboratory tests was to find an optimized pellet type for the large scale pellet test. Erosion, water storage and density were chosen as the three main evaluation criteria. Erosion; the sensitivity of the pellet to the inflowing water and the following material transport, is an important material parameter that must be considered. The ability of the pellet filling to store water is very important since it is desirable to avoid free water at the front of the backfill during the installation phase. It is also beneficial if the pellet filling has a high bulk density since the pellet filling density contributes to the overall backfill density.

Since the variation in bulk density was small between different pellet types, the choice of the pellet type was made based on the results in the erosion and water storage tests. The extruded pellet type showed better results regarding water storage and erosion than roller-compacted pellets. The extruded pellets with 10 mm diameter showed better erosion characteristics while the 6 mm had a better water storage capacity. The differences in erosion sensitivity were however small, especially after the initial phase when a channel is formed. Therefore the difference in water storage capacity is used as basis for the choice between the 10 mm and the 6 mm extruded pellets. The test results show that 6 mm extruded pellets have better water storage capacity than the 10 mm pellets. Hence the 6 mm extruded pellet was chosen as the preferred pellet type.

6 mm extruded pellets made from three different materials were tested: IBECO, ASHA and MX80. From these three materials IBECO and ASHA were chosen since MX80 is more sensitive to erosion.

4 Experiences from pellet production

Bentonite pellets for backfill of deposition tunnels were produced at different times as part of the subproject. Initially pellet trials where performed at HOSOKAWA BEPEX GmbH and AMANDUS KAHL GmbH & Co. Later a pellet press was rented for production at Äspö HRL.

4.1 Pellet production trials

Two different methods for pellet pressing, extrusion and compaction were tested. A lab compactor, CS25, from HOSOKAWA BEPEX GmbH was tested for manufacturing of roller compacted pellets.

Pellet presses from AMANDUS KAHL GmbH & Co were used for production of extruded pellets. Two different sizes of presses were tested, KAHL Flat Die Pelleting Press 14-175 with continuous raw material feed and a throughput of around 50 kg/h and KAHL Flat Die Pelleting Press 33-390, with manual raw material feed and a throughput of around 1,000 kg/h. The amount of pellets needed according to the reference design is app. 30 ton/day and hence the larger pelleting press best meets SKB's current capacity requirements.

Three different clay materials were used for manufacturing tests:

- **MX-80**. With granular size distribution of 0.05–1.0 mm and bulk density of 1,110 kg/m^3. For material characteristics, see Karnland et al. (2006).
- **ASHA NW-BFL-L.** With granular size distribution of 0.05–10.0 mm and bulk density of 1,320 kg/m^3. For material characteristics, see Sandén et al. (2013).
- **IBECO RWC-BF.** With granular size distribution of 0–5 mm and bulk density of 1,180kg/m^3. For material characteristics, see Sandén et al. (2013).

Using roller compaction, a too moist material could lead to overheating of the press. With extrusion on the other hand, pressing of dry material lead to overheating of the pellet press whereas a too moist material stuck to the auger and mixer. The water content needs to be optimized for each different pellet press and for each material.

At extrusion of ASHA, approximately 4 wt% of fine waste material was gained, the amount of fines increased by dryer raw material. The amount of fine waste material was negligible for IBECO. However it is possible to reuse the fine-material in the production process by mixing it with raw material.

4.2 Pellet production at Äspö

The conclusions from the laboratory tests in Andersson and Sandén (2012) resulted in a recommendation to use 6 mm extruded pellets for the large scale pellets tests. A KAHL Flat Die Pelleting Press 33-390 was rented at two different occasions for production of larger batches of 6 mm extruded pellets at the Bentonite Laboratory in Äspö, HRL. ASHA and IBECO material were used for the manufacturing tests.

The manufacturing encountered problems with overheating of the press, bentonite clogging to the feeding auger and die resulting in shutdowns. An important experience is that control and adjustment of the water content in the feeding material is essential to achieve a stable production process and pellets of high quality.

The choice of material feeding method is also important for gaining a stable production process. It was observed that an oppressive auger with horizontal feeding works better than an auger with an inlet angle of 60–70°, since raw material with high water content stuck to the latter one.

The thickness of the die was also identified as an important parameter. A thick die led to problems with material drying and clogging to the die with a following shutdown. Reducing the height of the die reduced the problems.

The overall conclusion from the pellet pressing tests is that pellet extrusion is considered an applicable and sufficiently robust method for production of bentonite pellets for backfill of deposition tunnels. Tuning of the production process, especially identifying the optimal water content, must be performed for every new material. This is however not considered a problem for the materials used in these experiments.

5 Large scale pellet test in the TASS-tunnel at Äspö HRL

A large scale pellet test was performed at Äspö HRL. An important function of the pellet fill is to buffer inflowing water and thereby delay the time to outflow at the backfill front. The main purpose of this test was to determine the time from the start of the backfill installation until water is expected to reach the front.

The work was carried out in accordance with the activity plan AP TD KBP1003-12-003. The activity plan is one of SKB's internal controlling documents.

5.1 Test layout

The test was performed in the TASS-tunnel at Äspö HRL. The test setup consisted of a central mould made of steel and wood, simulating a block stack, see drawing in Figure 5-1 and photos in Figure 5-2. The outer surface of the mould was covered with plastic and a bentonite mat in order to prevent water leakage to the inside of the mould. The test length was 5.5 meters.

An artificial water inflow was installed four meters from the front, see photo in Figure 5-2. A geo-textile stripe was placed over the point inflow in order to simulate a water bearing fracture zone crossing the tunnel. A water bearing fracture zone, or a crack, is a more likely inflow scenario than a large point inflow. The geo-textile, that was 10 cm wide, was applied from a point about one meter above the floor, up to the roof and down along the wall, ending one meter above the floor on the other side of the tunnel.

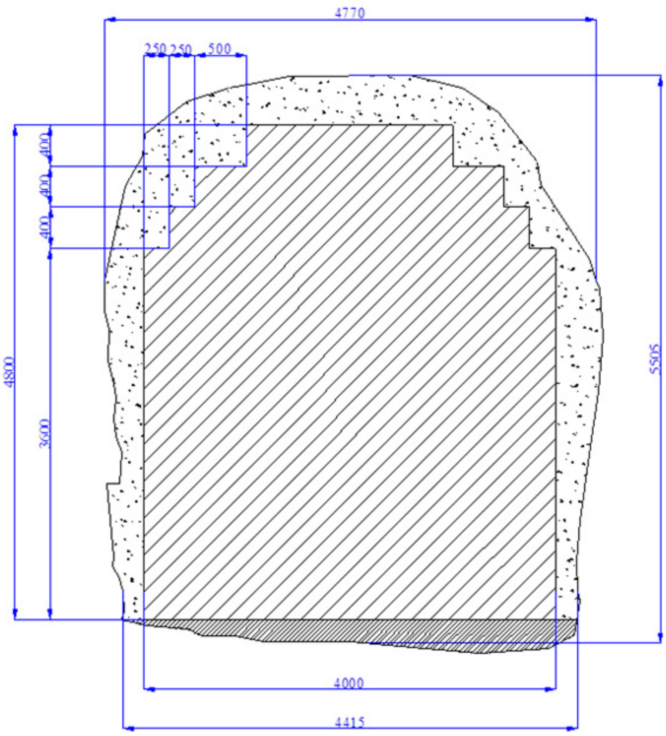

Figure 5-1. Schematic drawing showing the dimensions of the central mould and the approximate dimensions of the tunnel.

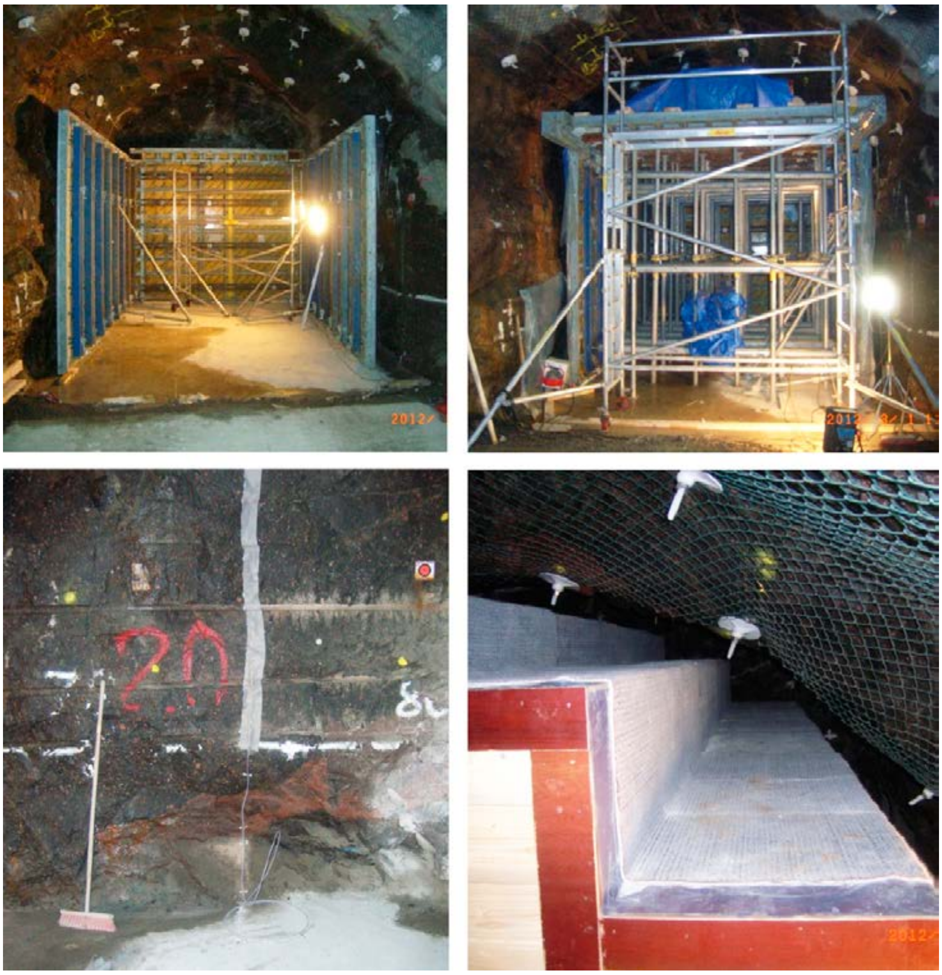

Figure 5-2. Photos from the preparatory work. Upper left and right: Installation of the mould simulating a stack of backfill blocks. Lower left: An artificial water bearing "fracture" (geo-textile) was installed four meters from the front. The "fracture" started one meter from the floor and went all way to the other side. Lower right: Photo showing the crown of the mould. The mould was covered with plastic and a bentonite mat in order to prevent leakage.

5.2 Installation and monitoring

5.2.1 Installation of pellets

Extruded bentonite pellets were chosen for the test, based upon the laboratory results presented in Andersson and Sandén (2012). The bentonite pellets were blown into the slot between the rock and the mould by use of shotcrete equipment. Due to an error in the estimation of required pellet volume in combination with limited access to pellets, the installation of pellets was divided into three different occasions during 2012. The main part of the filling consisted of pellets made of IBECO RWC BF 2011 but for a small part of the outermost filling, pellets made of ASHA NW-BFL-L 2010 was used, see Andersson and Sandén (2012) for pellet properties. The pellets installation was performed according to the following:

1. March 13. 14,560 kg IBECO RWC BF 2011. 6 mm extruded pellets.
2. September 5. 13,925 kg IBECO RWC BF 2011. 6 mm extruded pellets.
3. September 25. 5,232 kg ASHA NW-BFL-L 2010. 6 mm extruded pellets.

In total 33,715 kg of pellets was installed. The installed density was not measured, but it is assumed to be slightly lower than the bulk density for the IBECO pellets, 1,029 kg/m^3.

In order to end the installation as a vertical standing wall made of pellet, water was added at the nozzle positioned at the end of the tube coming from the shotcrete equipment. In total 882 litres of water was added.

The tunnel section used for the test was rather dry and it was assessed that the time between the different pellet installations did not have any major impact on the pellet properties. The mixing of different pellet materials was assessed not to affect the test result significantly since 6 mm extruded ASHA and IBECO have similar properties regarding water storing capacity and erosion (Andersson and Sandén 2012).

5.2.2 Water injection

During the test a constant flow of 0.5 l/min was applied into the tube connected to the artificial fracture. The water was mixed in a large tank placed in the tunnel. The water had a salinity of 1% (50/50 Na/Ca). The entire amount of pellets was installed before the water injection was started.

5.2.3 Monitoring

The following parameters were monitored during the test:

- Pressure to maintain water flow. The water pressure was registered every minute during the test.
- Amount of exiting water for the outflow rate to be monitored.

5.3 Sampling of the pellet filling

After water injection was switched off, a comprehensive sampling of the pellet filling was started. The sampling was done according to the following:

- The test was divided in nine sections, A to I, see Figure 5-3 for a schematic drawing. The first sampled section, A, was placed 4,800 mm from the innermost part of the mould and section H at the innermost part of the mould. The distance between each of the sections A to H was 600 mm. Section I was the innermost section i.e. the volume between the end of the mould and the end of the tunnel. Figure 5-4 shows a photo taken during the excavation of the test.
- The sampling of each section was made according to a 3D grid with the celldimensions 500 × 200 × 200 mm between the sampling points.
- During the work an assessment of the water content of the pellets was made i.e. the dry parts were not sampled since the pellets in dry parts collapsed and it was not possible to get correct positions.
- The water content was determined for all samples by calculating the weight loss after heating at 105°C for 24 hours. In total, the water content was determined on about 550 samples.

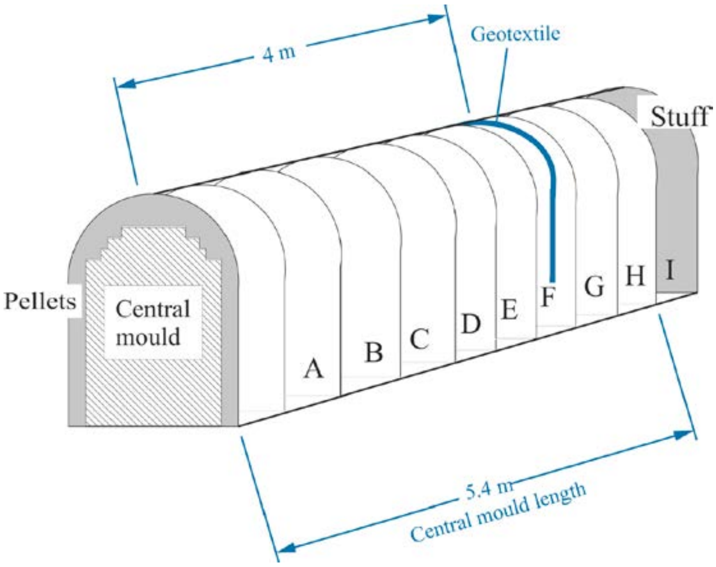

***Figure 5-3.** An overview of the sampling.*

Figure 5-4. *Photo taken during the excavation of the bentonite pellets.*

5.4 Results

5.4.1 Test start and monitoring

The test was started September 28 at 10:38.

Besides the registration of the water pressure build up during the test time, see result presented in Figure 5-5, the following observations were made during the test:

- First outflow noticed 2012-10-03 09:00, after 118.4 hours. Measured outflow was 0.21 l/min. The outflow could not be traced to a certain position.
- 2012-10-04 10:00. Measured outflow was 0.21 l/min. The outflow could not be traced to a certain position.
- 2012-10-05 09:00. Measured outflow was 0.21 l/min. The outflow could not be traced to a certain position.
- 2012-10-15 10:30. Measured outflow was 0.21 l/min. The outflow could not be traced to a certain position.

The water injection was closed 2012-10-15 14:00 after more than seventeen days of water injection. It was not possible to trace the outflow to a certain point. The outflow seemed, however, to mainly come from the right side of the test (the same side as where the water was injected).

5.4.2 Water pressure

The registered water pressure, see Figure 5-5, shows that there was a certain flow resistance during the whole test period also after the first outflow of water, which indicates that the inflowing water mainly has been stored in the pellet filling. A channel flow would result in very low flow resistance.

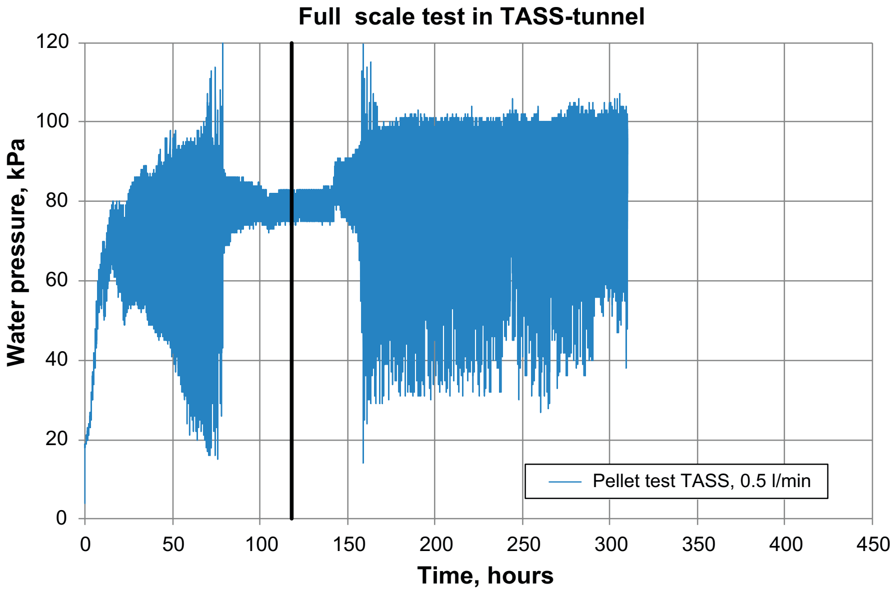

Figure 5-5. *Registered water pressure plotted versus time. The first water outflow was noticed 118 hours after test start (black line).*

The variations in pressure during test time, between 30 and 100 kPa, are probably partly due to the strokes of the water injection pump and partly due to internal piping in the pellet filling. An explanation for the more even pressure during the period between 75 to 150 hours after test start could be that channel flow partly has occurred during this time, resulting in less flow resistance. The water pressure was registered every minute during the test.

5.4.3 Water storing

The results from the determination of water content in the pellet filling are presented in Figure 5-6 and Figure 5-7. In the figures, the water content of the dry parts of the pellet filling (which was not sampled) is set to 20% which is approximately the same as the initial water content of the pellets with some variations between the different batches.

From Figure 5-6 and Figure 5-7 the following conclusions are made:

- The figures clearly shows that there has been an extensive wetting of the pellets on the right side (all sections), which is the same side as where the inflow point was positioned.
- In section A, B and C there are large wetted parts also on the left side. In section D, E and F, left side, there is some minor wetting mainly at the lower parts.
- The artificial fracture is positioned in section F, hence section F is the section which has been mostly wetted.
- The pellet filling in the uppermost (crown) region is only partly wetted. There are parts of the crown wetted in section B, C, E and F while section A, D, G and H are almost dry.
- The pellet filling between the innermost part of the mould and the tunnel end is partly wetted.
- The wetted parts of the pellet filling had water contents ranging between 25 and 75%.

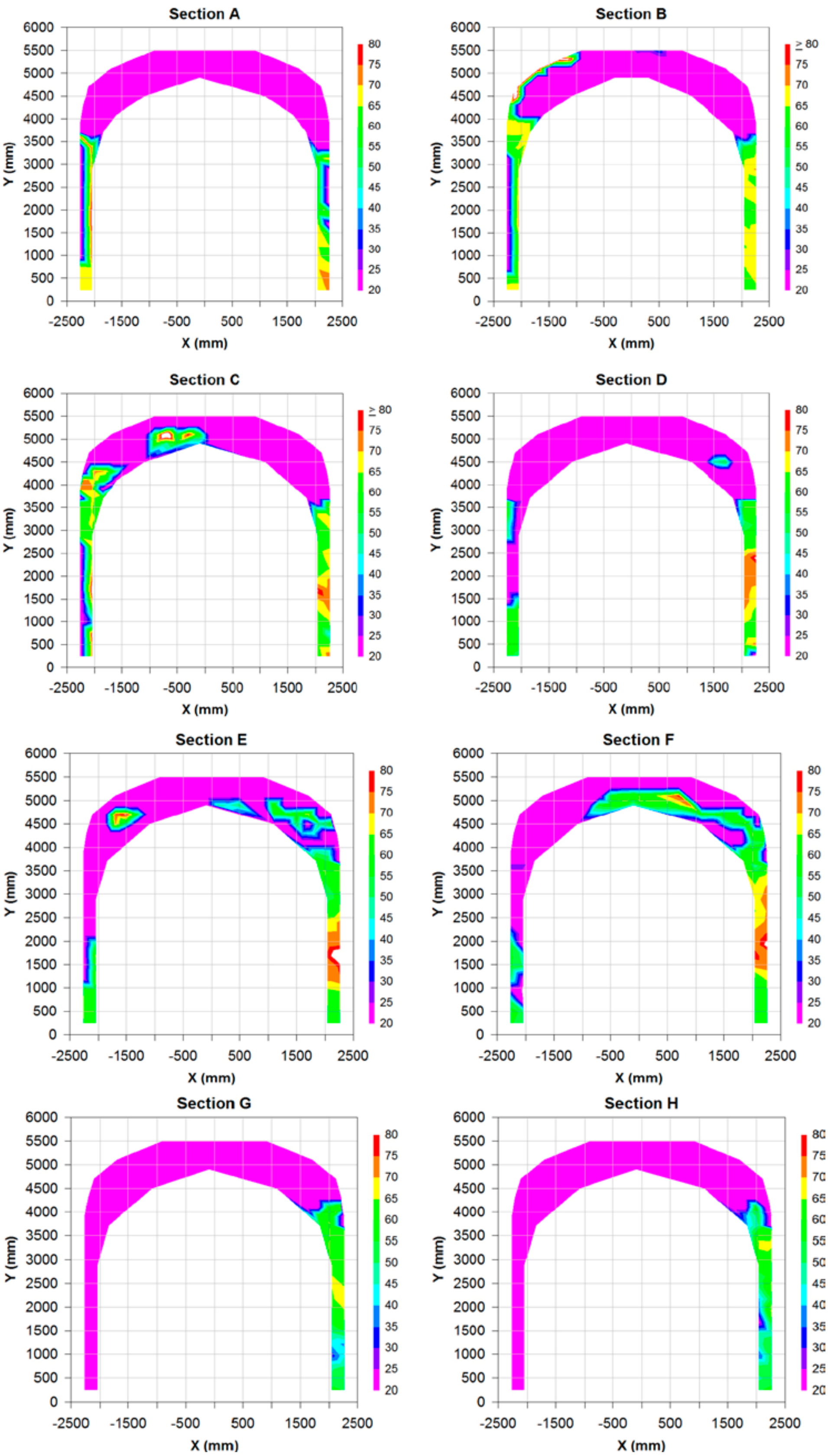

Figure 5-6. Figures showing the water content distribution of the pellets in the slot for the eight sections around the mould sampled.

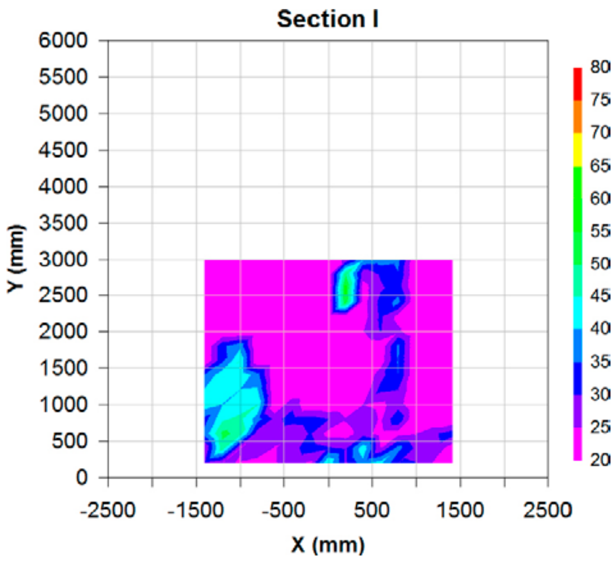

Figure 5-7. *Figure showing the water content distribution of the pellets in the slot between the tunnel end and the mould.*

5.5 Summary and conclusions

From the test the following conclusions were drawn:

- In total 33,715 kg of pellets was installed. In the pellet filling there was about 45% macro voids (empty voids between the individual pellets) where water could be stored. This means that theoretically about 15 m^3 of water could be stored in the pellet filling. By the end of the test more than 12 m^3 of water had been injected. During the first 118 hours 3.5 m^3 was stored in the pellet fill. From the start of the outflow until the test was closed around 5 m^3 of water was stored in the pellet fill. This makes a total of about 8.5 m^3, see Figure 5-8. This means that about 56% of the pellet filling was wetted which is assessed to be rather close to the results obtained from the sampling, see Figure 5-6 and Figure 5-7.
- The test result shows that the pellet fill can withstand a few days of interruption in the backfilling process before outflowing water reaches the backfill front, by a combined inflow of 0.5 l/min. A combined inflow is denoted by several point flows within a limited area that together forms an inflow of 0.5 l/min.
- This full scale test verified the results from the scale tests (Andersson and Sandén 2012) that the water storing continues also after the first breakthrough of water at the front.
- The water storing mainly took place at the walls leaving the crown almost dry, except for the areas close to the geo-textile stripe. This probably depends partly on gravimetrical effects i.e. the water flows downwards in the geo-textile. Another explanation could be that the density of the filling at the top is lower, which leads to that water flows easier in this part. When the water reaches the denser filling at the lower parts of the wall, the bentonite gets more time to swell and seal and by that store the water more effectively.

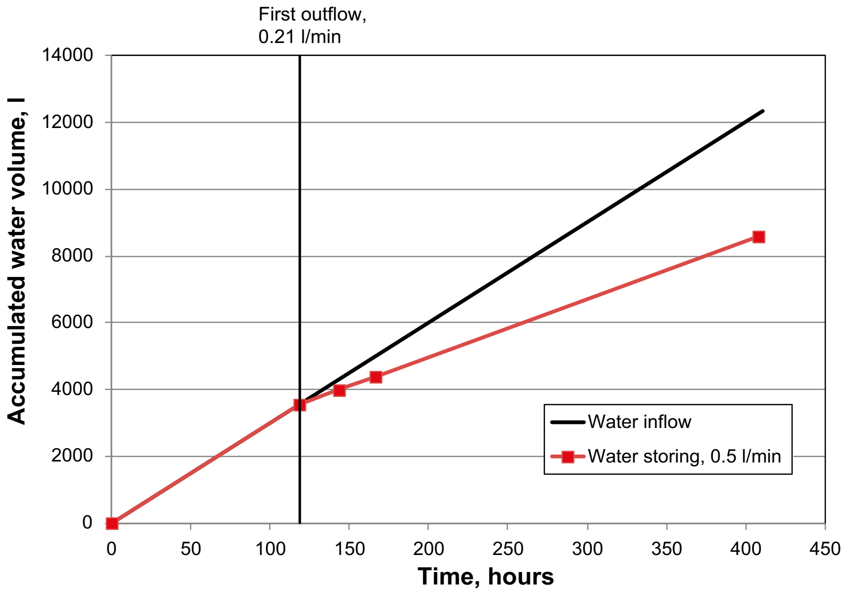

Figure 5-8. *The accumulated water inflow and water storing plotted versus time. After about 118 hours water starts to flow out but about 60 percent of the inflowing water continues to be stored in the pellet filling.*

6 Main conclusions and further recommendations

6.1 Conclusions

The general conclusion from the laboratory pellet tests is that extruded pellets with a diameter of 6 mm seem to have the best overall characteristics. Regarding materials ASHA and IBECO were superior MX-80. The extruded pellets were the most resistant to erosion, but all material and pellet types are within the limits of the theoretical model describing the erosion rate by Sandén and Börgesson (2010). The extruded pellets also had a higher water flow resistance and seemed to decelerate the water front better than the compacted pellets according to the comparisons in the initial water storing tests. Installation tests with shotcrete equipment showed that extruded pellets were much more durable than compacted pellets.

There are mainly two techniques commonly used in the industry to produce compacted pellets of various materials to be considered for backfill pellets; roller compaction and extrusion. In the pellet pressing tests a lot of 6 mm extruded pellets were pressed since it was the recommended pellet type based on the laboratory tests. The overall conclusion from the pellet pressing tests is that pellet extrusion is considered an applicable and sufficiently robust method for production of bentonite pellets for backfill of deposition tunnels. Tuning of the production process, especially identifying the optimal water content, must be performed for every new material. This is however not considered a problem for the materials used in the experiments.

The large scale test also verified the conclusion from previous studies done in 1/12 and ½ scale (Dixon et al. 2008) that the pellet fill can withstand a few days of interruption in the backfilling process before outflowing water reaches the backfill front, by a combined inflow of 0.5 l/min. A combined inflow is denoted by several point flows within a limited area that together forms an inflow of 0.5 l/min.

One of the objectives of the subproject was to find an optimized pellet type. Based on the laboratory tests the 6 mm extruded pellets was chosen as the preferred pellet type for the large scale test. The large scale test verified that the pellet type has desirable characteristics regarding erosion and water storing capacity.

6.2 Further recommendations

The shotcrete equipment used to install pellets in the gap between the deposition tunnel walls and the backfill blocks can be used for installation of extruded pellets with an acceptable crushing rate. However the method is not applicable for roller compacted pellets. The equipment used has a relatively low capacity and it might not fulfil the requirements regarding installation time. Furthermore lots of dust arose during the large scale pellet installation test, which could cause problems with i.a. measurement equipment. Hence it is recommended to further study and develop technologies for pellet installation. One method that has been discussed is spiral conveyor.

Based on the laboratory tests and full scale tests extruded 6 mm pellets are considered as a good backfill pellet candidate. Next interesting step is installation together with backfill blocks in a field situation to be able to study how well the pellets buffer inflowing water during installation.

References

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

Andersson L, Sandén T, 2012. Optimization of backfill pellets properties. ÅSKAR DP2. Laboratory tests. SKB R-12-18, Svensk Kärnbränslehantering AB.

Dixon D, Lundin C, Örtendahl, E, Hedin M, Ramqvist G, 2008. Deep repository – engineered barrier systems. Half scale tests to examine water uptake by bentonite pellets in a block-pellet backfill system. SKB R-08-132, Svensk Kärnbränslehantering AB.

Dixon D, Sandén T, Jonsson E, Hansen J, 2011. Backfilling of deposition tunnels: Use of bentonite pellets . SKB P-11-44, Svensk Kärnbränslehantering AB.

Johannesson L-E, Sandén T, Dueck A, Ohlsson L, 2010. Characterization of a backfill candidate material, IBECO-RWC-BF. Baclo Project – Phase 3. Laboratory tests. SKB R-10-44, Svensk Kärnbränslehantering AB.

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

Posiva, 2012. Safety case for the disposal of spent nuclear fuel at Olkiluoto – Synthesis 2012. Posiva 2012-12, Posiva Oy, Finland.

Sandén T, Börgesson L, 2010. Early effects of water inflow into a deposition hole. Laboratory tests results. SKB R-10-70, Svensk Kärnbränslehantering AB.

Sandén T, Börgesson L, Dueck A, Goudarzi R, Lönnqvist M, 2008. Deep repository – Engineered barrier system. Erosion and sealing processes in tunnel backfill materials investigated in laboratory. SKB R-08-135, Svensk Kärnbränslehantering AB.

Sandén T, Olsson S, Andersson L, Dueck A, Jensen V, Hansen E, 2013. Investigation of backfill candidate materials. SKB R-13-08, Svensk Kärnbränslehantering AB.

SKB, 2010a. Design and production of the KBS-3 repository. SKB TR-10-12, Svensk Kärnbränslehantering AB.

SKB, 2010b. Design, production and initial state of the backfill and plug in deposition tunnels. SKB TR-10-16, Svensk Kärnbränslehantering AB.