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Deliverable 4 of Module 1
Work Packages 4.1 and 4.2

Report on In-Situ Test Configurations

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EXECUTIVE SUMMARY

This report describes the work performed for the full-scale mockup grout injection backfill test (part 1 of Work Package 4.1) and the in-situ demonstration of sealing performance in a vertical borehole (Work Package 4.2) within Module 1 of the ESDRED project. It also describes the design of the steel support structure and the selection of the swelling material for the PRACLAY seal (part 2 of Work Package 4.1).

The operational target of the mockup backfill test was to apply, on a 30 m long full-scale mockup, the grout backfill technique developed in Module 1 Work Package 3 hereby using the same specific grout premix material (but possibly a different W/C ratio). Hereby, the test objectives were to demonstrate the feasibility of the grout injection technique for backfilling an annular gap under thermal load conditions, and more in general, to evaluate the results in view of a possible application in real repository conditions. The injection test was executed on April 8th 2008. From the test results, it can be concluded that the application of the technique was essentially successful, but not fully. The injection was performed at a satisfactory rate, the annular gap was as good as completely filled and the mockup design proved to be very robust, but the grout did however fail to become hard as it should. The test was largely successful in providing a broad information basis which can be used for the next phases in the development of the grout backfill technology. The test allowed to monitor and analyze, on a 1/1 scale, the thermo-mechanical dynamics of the grout injection process, the actions performed by the operators and the involved operational safety hazards. Also, it gave a better insight in the logistical needs behind the backfill operation. A plausible explanation for the failure of the grout to become hard was derived and a remedy was proposed.

The general objective of the in-situ sealing test at Mont Terri URL was to confirm, under representative in-situ conditions, the characteristics of clay/sand mixtures as studied in preceding laboratory investigations in Module 1 Work Package 2 and 3. The four test seals installed at Mont Terri are currently nearing a state of full saturation, more than 2 years after water injection was first started. These long times to reach saturation were predicted from a mockup simulation in the GRS laboratory in Braunschweig. The operations at Mont Terri have so far been successful. After achieving full saturation, the gas break-through performance of the seals will be tested. As not excluded already at the beginning of ESDRED, this activity will fall outside of the contractual time framework (i.e. until February 1st 2009). The ongoing activities, however, will be financed on national basis. At the end, GRS will write a publishable final report covering the whole SB experiment over its entire duration. In addition, GRS will also update this report including the results and conclusions of the gas injection tests (if available within a reasonable time span after the construction of the PRACLAY seal.

The main objectives of the PRACLAY seal test within the scope of ESDRED were to select the material for the hydraulic seal and to design and construct a structure in which the interaction of the seal material with the host rock can be tested. The evolution of the swelling material after the installation of the seal is not within the contractual scope of ESDRED. At present, the design of the seal steel support structure and the selection of MX-80 as the swelling material have been achieved. The actual in-situ installation of the seal remains to be done. Due to a rescheduling of works, this activity will fall outside of the contractual time framework of ESDRED. The installation is now scheduled for the second quarter of 2009. To abide to its contractual obligations, EURIDICE will provide an update of the present report to include a description of the in-situ installation of the seal.

1 INTRODUCTION

1.1 Main objectives of Work Packages 4.1 and 4.2

This report describes the work performed for the full-scale mockup grout injection backfill test (part 1 of Work Package 4.1), the in-situ demonstration of sealing performance in a vertical borehole at the Mont Terri URL (Work Package 4.2), and the design of the steel support structure and the selection of the swelling material of the Seal in the PRACLAY gallery of the Mol URL (part 2 of Work Package 4.1).

The main objectives of the mockup backfill test (part 1 of Work Package 4.1) were to demonstrate the feasibility of the grout injection technique for backfilling an annular gap under thermal load conditions, and more in general, to evaluate the results in view of a possible application in real repository conditions.

The main objective of the in-situ sealing test at Mont Terri (Work Package 4.2) was to confirm, under representative in-situ conditions, the characteristics of clay/sand mixtures as studied in preceding laboratory investigations in Module 1 Work Package 2 and 3. The gas break-through performance will be tested outside of the ESDRED time framework, but the results will be made available and published after termination of the field work within the framework of the respective national German research program.

The main objectives of the PRACLAY seal test within the scope of ESDRED were to select the material for the hydraulic seal and to design and construct a structure in which the interaction of the seal material with the host rock can be tested. The evolution of the swelling material after the installation of the seal is not within the contractual scope of ESDRED.

Due to a rescheduling, the actual in-situ construction of the PRACLAY seal will fall outside of the ESDRED project time frame. Nevertheless, it is envisaged to update the present report to include a description of this construction, which is scheduled for the second quarter of 2009.

1.2 Relation with other Module 1 Work Packages

Work Packages 4.1 and 4.2 are the sequel of the demonstration work on buffer or seal construction within Work Package 3, but only for O/N, EURIDICE and the GRS. The other concerned Module 1 partners, ANDRA and NAGRA, have performed their demonstration work all within Work Package 3 and have therefore, apart from the final reporting, finished their work within Module 1. The NDA (formerly NIREX) have performed their work within Work Package 5. Nevertheless, both in terms of human resource and expenses, the extent of Work Packages 4.1 and 4.2 is comparable to Work Package 3.

1.3 Structure of the Deliverable 4 document

Deliverable 4 contains three major report Sections, each one describing the work performed within Work Package 4.1 part 1, Work Package 4.2 and Work Package 4.1 part 2 respectively.

Each of the major report Sections is structured around the following subjects:

1. Description of test configuration
2. Listing of test objectives
3. Description of the performed test activities
4. Evaluation of test results and conclusions
5. Possible improvements for the future

2 FULL-SCALE MOCKUP BACKFILL TEST (BY O/N)

2.1 Test installation and backfill material used

2.1.1 Recall of the HLW disposal concept

The design for the disposal of HLW supported by ONDRAF/NIRAS is based on the so-called Supercontainer concept. In the reference design version of this concept, the waste is encased in a 30 mm thick carbon steel overpack, which is subsequently fitted into a 70 cm thick concrete shell, in its turn enveloped by an 8 mm thick stainless steel liner. With a diameter of about 2 m and a length between 4 m and 6 m, depending on the type of waste, the Supercontainer weight ranges from 30 to 60 tons.

In the repository, the Supercontainers will be emplaced, one after the other, in a drift of approximately 1 km long. This drift will be excavated by use of a tunnel-boring machine and be lined with concrete wedge blocks; this is a much-used technique in modern tunnel construction. The drift will be outfitted with a floor, specifically designed to provide a path for the transportation vehicles as well as serve as a mechanical support the disposed Supercontainers.

Figure 2-1 shows a radial cross-section of such a HLW disposal gallery. The void between the Supercontainer, the floor and the gallery lining is to be filled with a specific backfill material.

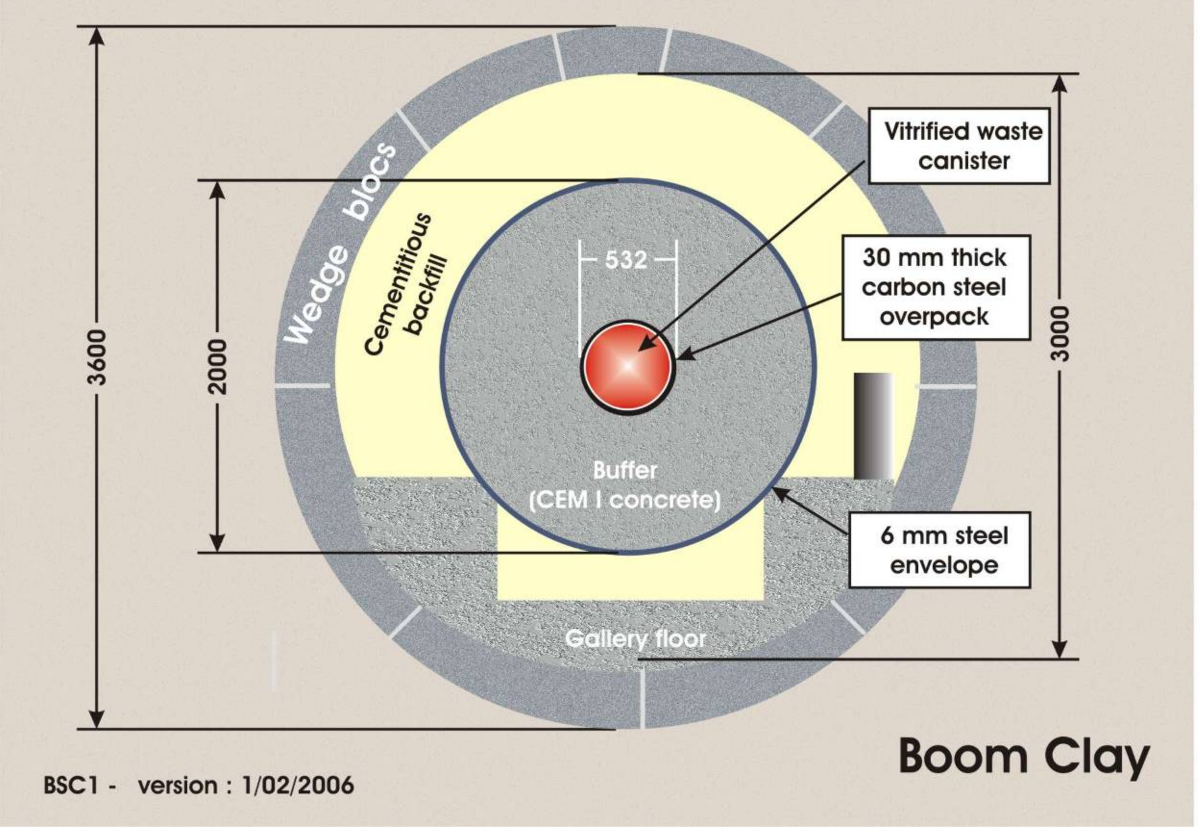


Figure 2-1 : Radial cross-section of a HLW disposal gallery in the O/N concept

2.1.2 Backfill materials and emplacement techniques

Backfill material

For the backfill test of Work Package 4.1, only the solution based on the injection of a grout was tested. The composition of the dry premix of this specific backfill material was not changed from the one developed in Work Package 3. The dry premix material, which only has to be mixed in a certain proportion with water to obtain the grout, is composed of clinker cement, calcium carbonate (limestone) powder, fine quartz sand and a limited addition of a polycarboxylate ether-based superplasticizer.

The development of this specific material had been a key process within Work Package 3 entrusted to BASF Construction Chemical Belgium, a company specialized in developing additives for concretes. The same company was also the provider of the grout material for the test of Work Package 4.1.

In the Work Package 3 backfill test, a water/cement (W/C) ratio of 1.34 had been used. For the backfill test of Work Package 4.1, in a first approach, a similar W/C ratio was to be used, but the actual value was left over to the decision of the BASF experts present during the test, based on samples taken of each batch of grout.

Emplacement technique

In the repository, after a predefined number of Supercontainers have been disposed, the gallery section is sealed by means of a casing. The casing is penetrated by an injection nozzle at the bottom and a vent nozzle at the top. On the accessible gallery side, the injection nozzle is connected to the grout pumping system. On the enclosed side, the nozzle is connected to the injection tube, located at the bottom of the void.

Before the emplacement of the Supercontainers, the gallery section was prepared by removing all materials that should not be left behind (electric wiring, lighting armatures, compressed air ducts, ventilation hoses or ducts, …) and by installing the necessary grout injection tubing.

The location of the injection tube at the bottom of the void is done with the aim to maximize the homogeneity of the backfill and to avoid problems with hardening of parts of the grout during the injection. By injecting from the bottom, there will be a constant mixing of the earlier pumped in grout with the later pumped in grout. Openings at regular intervals are foreseen in the floor to allow the grout level to rise from the space under the Supercontainers to the space above the floor. A location of the injection tube at the bottom of the void also avoids that there would at any be a free fall of the grout into the void, hereby potentially invoking segregation.

This injection principle had successfully been tested in Work Package 3. Based on experience from this previous test, it was decided to take an injection tube with a length of 25 m, which is 85% of the length of the gallery section. This means that the grout is injected at the back-end of the gallery section. The injected material will therefore propagate from the back to the front end of the gallery section, resulting in a certain incline of the grout level. This physical phenomenon should facilitate the expulsion of the remaining air (and water) through the vent tube located at the top of the front-end casing.

2.1.3 Description of the Mock-up and its construction

The backfill test of Work Package 4.1 was performed on a 30 m long full-scale representation of a section of a disposal gallery in which a row of approximately 8 Supercontainers with vitrified HLW have been disposed.

The construction of the mockup was the subject of a public tender (negotiation procedure, publication in the Belgian official journal "Bulletin der Aanbestedingen / Bulletin des Adjudications" on July 25th 2006). The contract was awarded in May 2007 to SMET-TUNNELLING, a company specialized in tunnel constructions and located nearby the EURIDICE site.

Because of its dimensions and weight, it was clear that the mockup would not fit in any of the existing facilities on the EURIDICE site. Therefore it was decided to construct the mockup on a vacant piece of land, accessible by road and able to carry the weight of the mockup. A new shed was to be built around it, to protect it from open air weather conditions. The chosen location is about 50 m to the Southeast of the first shaft of the Mol URL.

The construction work spanned the time period from June 2007 to January 2008. Figure 2-2 shows an as-built overview plan of the whole mockup. Figure 2-3 gives the details of the front and back-end of the mockup and Figure 2-4 gives the radial dimensions, both with some explanations.

The main components of the mockup are:

- one concrete support slab
- 13 rings of reinforced concrete jacking pipes of 3 m internal diameter and about 2.3 m length (note that these pipes contain an internal steel sheath over their whole length)
- 14 concrete support sockets of 4.5 m width
- a concrete floor similar to the one in the HLW disposal gallery of the repository (this floor is constructed after the concrete pipes are fixed)
- 2 carbon steel tubes of 2 m outer diameter, 5 mm thickness and about 15 m length
- one carbon steel tube of 0.5 m internal diameter and about 30 m length (composed of a number of welded tube sections)
- 4 axial heater elements of about 30 m length (these are magnesium oxide resistor cables)
- 2 closure lids, one for the front-end and one for the back-end side of the simulated gallery
- a bulk quantity of fine sand, to fill up the inside of the 2 m diameter pipes (for thermal inertia)
- one carbon steel tube of 4" outer diameter and about 27 m long for normal grout injection, and three pairs of carbon steel tubes as backup in case of failure of the normal injection path.

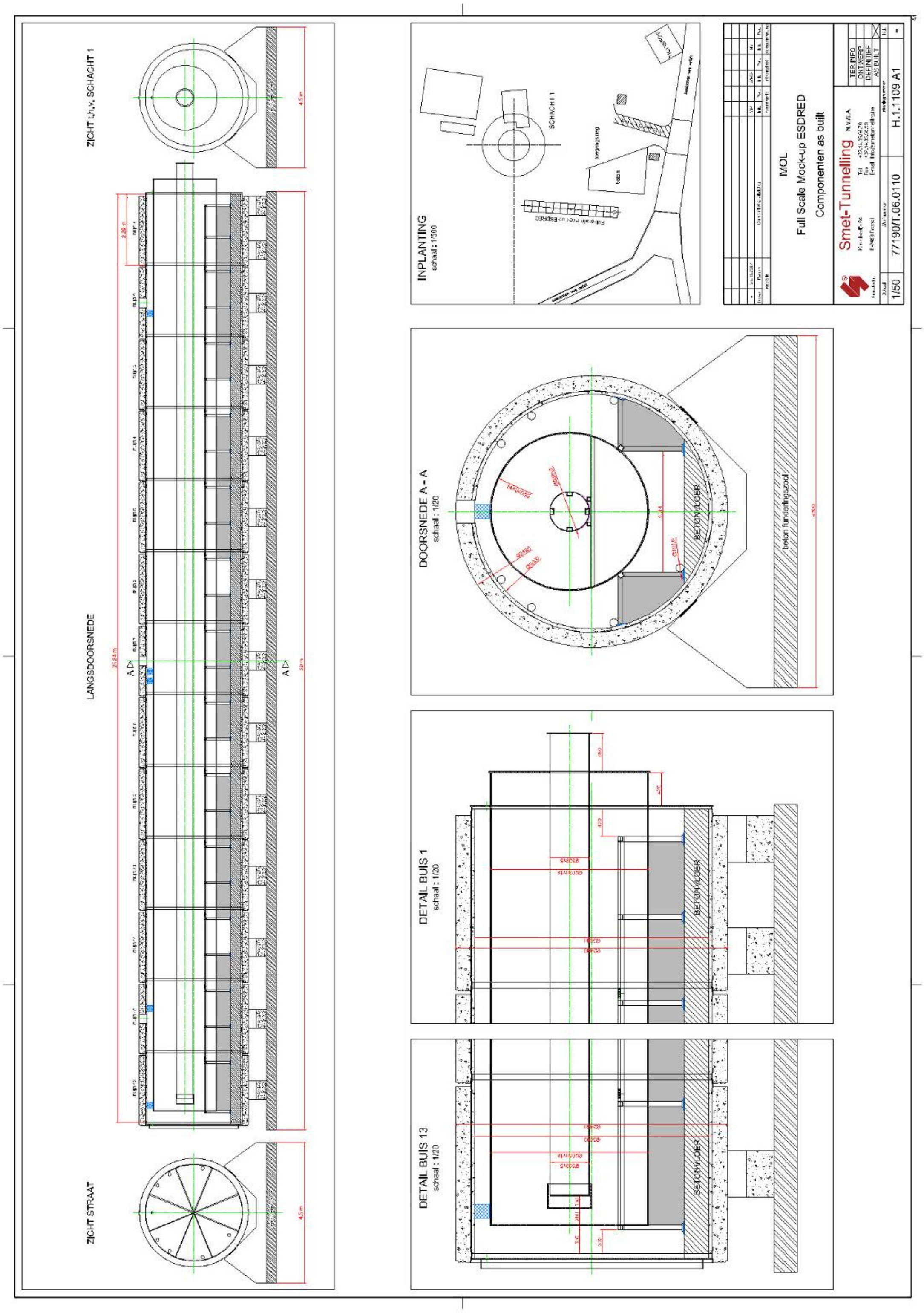


Figure 2-2 : **As-built overview plan of the full-scale mockup for backfill grout test**

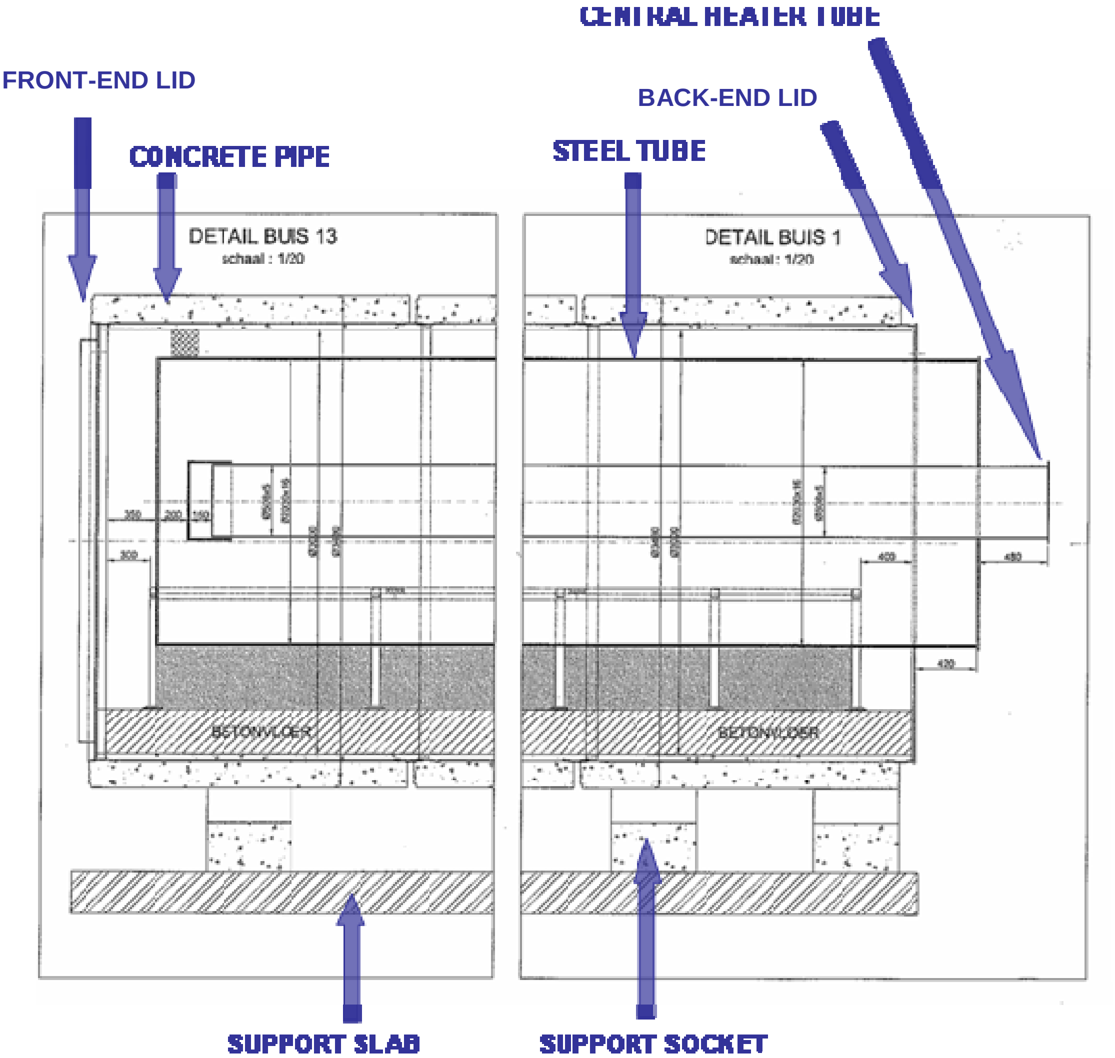


Figure 2-3 : **Axial cross-section of the front and back-end side of the full-scale mockup**

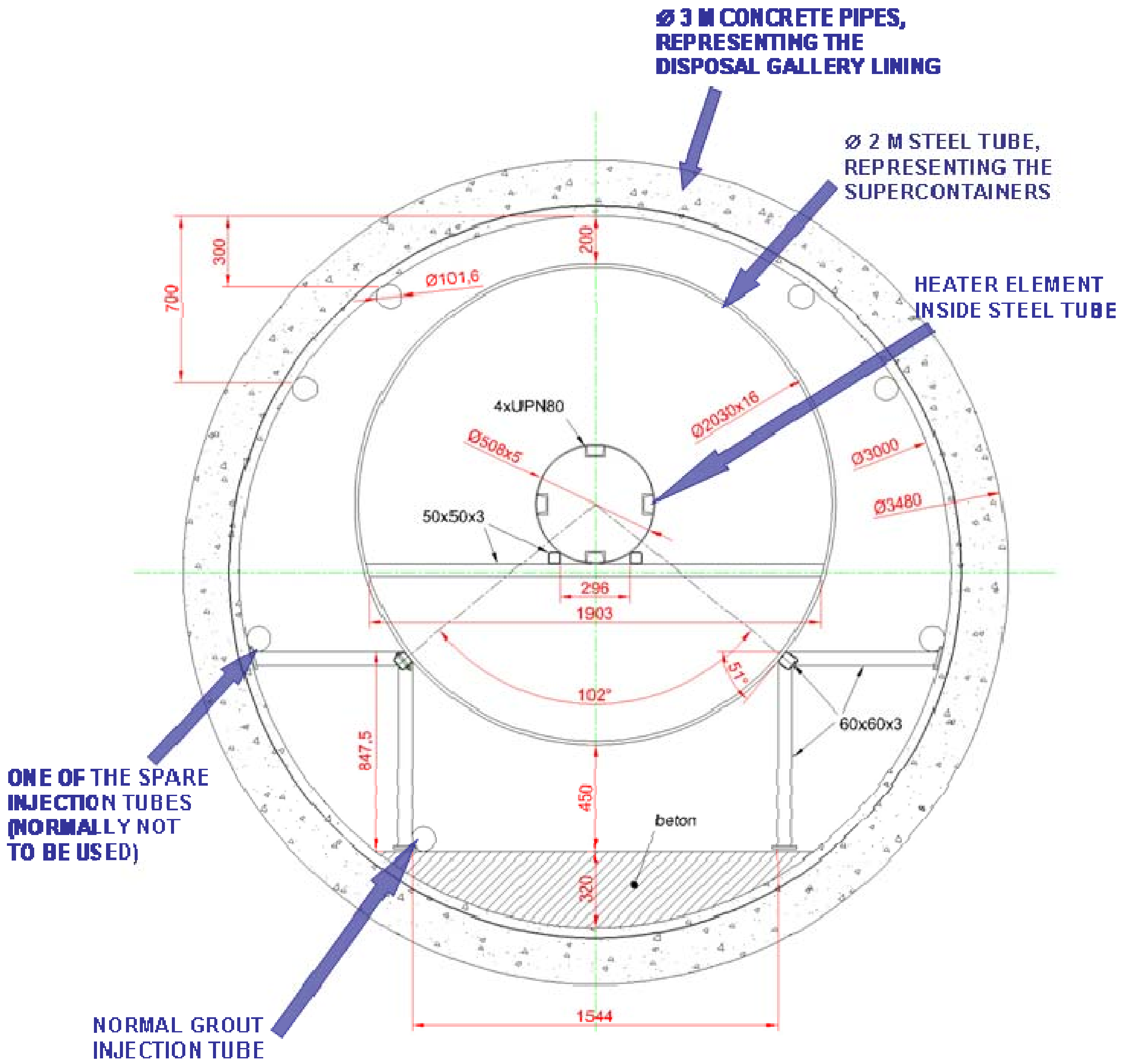


Figure 2-4 : Radial cross-section of the full-scale mockup

The lining of the disposal gallery is represented in the mock-up by a row of 3 m internal diameter concrete pipes. Each of the pipes rests on a concrete support socket, which in their turn are resting on the support slab. Figure 2-5 illustrates the construction of the row of concrete pipes simulating the disposal gallery lining. The steel sheathing inside the concrete pipes, which was exposed at the pipe ends, were welded together, resulting in a fully hermetic structure.

Before inserting the 2 m diameter steel tube representing the disposed Supercontainers, the floor was constructed. The shape of this floor is the same as in the actual reference HLW disposal gallery design. A 102° angle determines the mechanical support of the Supercontainers by the left and right floor sockets. The resulting minimum gap space, at the top of the steel tubes, is 20 cm. The two pictures in Figure 2-6 illustrate the construction of the floor. Openings at regular intervals are foreseen in the floor sockets to allow the grout level to rise from the space under the Supercontainers to the space above the floor (see Figure 2-7).

Figure 2-5 : Construction of outer lining (pictures taken Sept 5th 2007)

Figure 2-6 : Construction of floor (pictures taken Sept 21st 2007)

The next step, before inserting the 2 m steel tubes, which would make accessibility more difficult, the instrumentation was installed (by EURIDICE personnel). Figure 2-8 shows a picture.

Figure 2-7 : Example of an opening in the floor sockets to allow the grout to rise from under the Supercontainers (picture taken Oct 18th 2007)

Figure 2-8 : Installation of the temperature and strain sensors in the middle section of the mockup (picture taken Oct 18th 2007)

Main objectives of the instrumentation were to follow the evolution of temperatures inside the mockup and the level of the grout during the injection.

The mock-up was instrumented with the following sensors:

- temperature sensors (type T thermocouples), to follow the rise of the grout level and its shape (grout is of much colder temperature) during the injection phase and to follow the temperature distribution within the backfill after the injection phase;
- ultrasonic level sensors, to give an accurate level measurement when the grout level is approaching the top of the void during the injection phase;
- thermal needles (model TP09 from Hukseflux), to measure the thermal conductivity after the grout has set, i.e. when temperatures have stabilized;
- vibrating wire strain gauges (type TES 5.5 from Gage Technique), strategically placed, to give an indication of the process of the hardening of the grout;
- TDR sensors to monitor the (decrease in) water content during grout curing.

Figure 2-9 provides an overview of the instrumentation layout. In radial sense, three cross-sections (front, middle and end) were outfitted with a temperature sensor cobweb.

The sensors are connected to a data logging system based on Campbell Scientific data loggers (suited for vibrating wire sensors, TDR probes and thermal conductivity sensors). The data logging system has to provide the following functions:

- autonomous data logging with regular data transfer (through Ethernet connection) of the measured data to PC;
- real-time visualization (mainly temperature and level) during critical phases (grout injection).

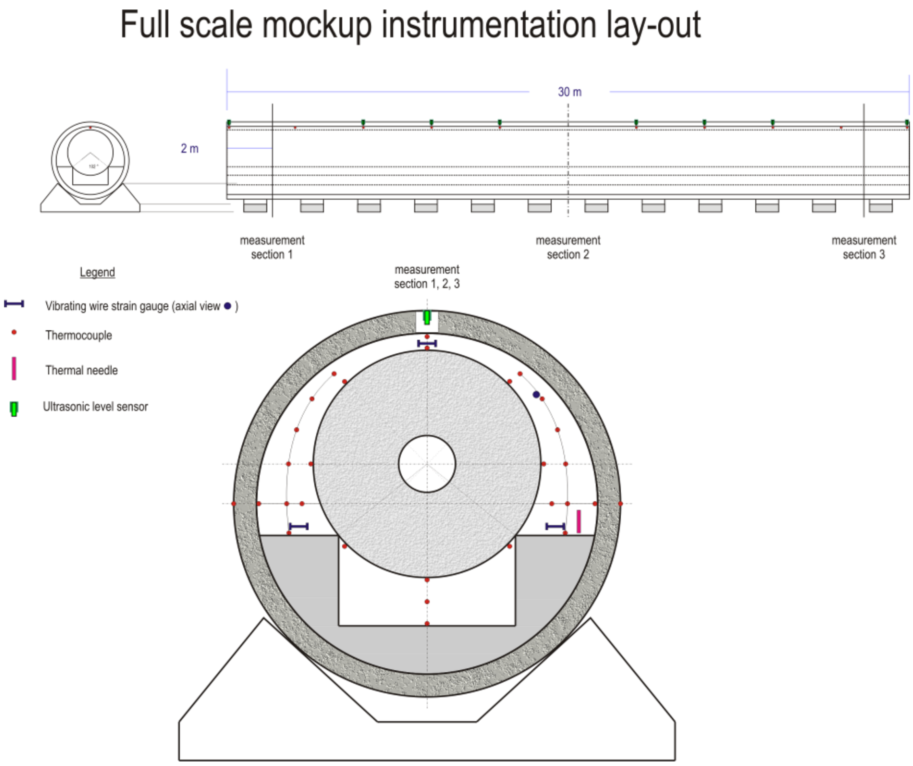


Figure 2-9 : Overview of the instrumentation in the mockup

As there was no space for welding inside the mock-up, the 2 m outer diameter steel tubes were welded together outside the mock-up, and then gradually inserted into the mockup (Figure 2-10). A number of support blocks was mounted between the top of the steel tube and the inside of the concrete pipes to counter any buoyant forces on the tubes during the grout injection and thus to ensure its mechanical fixation. Inside the 2 m diameter steel tubes, the central heater was installed. The structural elements of the heater consist of a 0.5 m diameter tube into which 4 U-profiles are welded (Figure 2-11). Inside each profile is a heater cable (resistance), which is the actual heating element, and a thermocouple to protect the heater cable from overheating. In total, the heater capacity is 25 kW.

The heater was controlled by a PID controller (input provided by thermocouples mounted on the surface of the 2 m steel tube). After the installation of the heater, the 2 m steel tube was filled with fine sand, to simulate the thermal inertia of the mass of the disposed Supercontainers.

One carbon steel tube of 4” outer diameter and about 27 m long was installed on the bottom of the floor insert. This is the normal grout injection line. Three 3 pairs of carbon steel tubes were installed in the upper part of the void. These are the backup injection lines, to be used only in case of a failure of the normal injection line. Different lengths were chosen for these tubes; the pair of tubes lying on the floor are 15 m long, the tubes at the higher level are 27 m long and the highest tubes are only 3 m long.

The mock-up was hermetically closed by two steel lids bolted on the rim of the concrete pipes. A vent nozzle of the same diameter was installed in the top of the front lid, so that the remaining air in the void could escape during the filling. The protruding tubes and vent nozzle were fitted with ball valves. A watertightness test was conducted in December 2007. The void was filled with water and checked for leaks. The water was left in the mockup for several weeks. In the meantime, a shed was built around the mockup (see Figure 2-12). No leaks were detected and the water was led down in January 2008. A layer of isolation material was placed around the mockup to prepare it for the heated phase (see Figure 2-13).

On February 9th 2008, the central heater was switched on. The temperature conditions inside the mockup increased gradually until a stable 60°C on the surface of the 2 m diameter steel tube was reached after about 6 weeks. The 60°C represents a hypothetical maximum surface temperature of a Supercontainer lying in a non-backfilled disposal gallery. It should be mentioned that, in practice the PID controller of the heater was not used, as the PID thermocouple sensor was quite distant from the heater and initially this caused the heater elements to operate at full power, thereby reaching quickly the 200°C protection limit, at which an interlock automatically switched off the power. Hence, each switch-on of the heater power was performed manually instead of automatically.

Figure 2-10 : Insertion of the 2 m diameter steel tubes (picture taken Oct 18th 2007)

Figure 2-11 : The heater tube being prepared

Figure 2-12 : The shed around the mockup (picture taken January 15th 2008)

Figure 2-13 : The mockup being isolated (picture taken February 25th 2008)

2.2 Objectives of the test

2.2.1 Requirements for the HLW disposal gallery backfill

In the O/N disposal concept for HLW, the backfill component fulfills two ***functions***:

1. *The primary function of the backfill is to prevent a cave-in of the disposal drift, which might damage the Supercontainer or distort the host rock surrounding the drift.*

   If the space between the Supercontainer and the wall has been sufficiently filled up with solid material, the inevitable loss of integrity of the wall will occur without causing damage to the Supercontainer or to the host rock. It is not a function of the backfill to provide direct mechanical support to the drift wall.

2. *A secondary function of the backfill, applicable only to the disposal of spent fuel, is that the backfill minimizes the existence of potential escape paths out of the Supercontainer for the filler material present around the fuel assemblies.*

   By attributing this function to the backfill, the designers want to minimize the probability that any filler material around the fuel assemblies would escape and consequently be replaced by incoming water. The presence of water around enriched uranium material is an undesirable situation. Note however, that the direct disposal of spent fuel in Belgium is not certain. There is currently a moratorium on the reprocessing of spent fuel, but it is possible that this is lifted in the future.

Both functions can be achieved by filling up the void space around the disposal package and in the disposal gallery with a solid incompressible material.

Next to these functions, there are also ***constraints*** on the backfill component. Together, the functions and the constraints determine the requirements for the backfill component. Two types of constraints can be discerned: (1) constraints related to (long-term) safety, (2) constraints related to feasibility.

The ***safety constraints*** come from the consideration that the backfill should not disturb the functioning of the other repository components. As such, the following *long-term safety constraints* have been established:

1. *The backfill may not disturb the corrosion-protective characteristics of the environment around the overpack, established by the Supercontainer.*

   Therefore, the backfill may not contain aggressive species that are known to be corrosive to iron, such as reduced sulfur species or chlorides, nor may the backfill degrade the high alkaline nature of the overpack environment.

2. *The backfill may not act as a thermal isolator around the disposal package.*

   The temperature of the overpack must remain limited to 100°C. Therefore, the thermal conductivity of the backfill should be sufficiently high.

3. *The backfill may not disturb the retention characteristics of the host rock by introducing organic materials that can give rise to the formation of migration-enhancing complexes between radionuclides and soluble organic compounds.*

   Especially the use of cellulose-based materials in the backfill should be avoided. In a cementitious backfill, cellulose-based materials could be present through the used superplasticizer. For instance, the so-called first generation and second generation superplasticizers are cellulose-based.

4. *The backfill may not jeopardize the mechanical stability of the disposal cell by excessive expansion or shrinkage with respect to the disposal drift wall. Nor may it chemically attach the material of the disposal drift wall.*

Therefore the backfill material should have a thermal expansion coefficient which is comparable or lower than the one of the drift wall material (concrete wedge blocks) and exhibit little or no swelling. Moreover, it should be chemically inert with respect to this material.

Moreover, the emplacement of the backfill should be operationally feasible. This has led to the following operational ***feasibility constraints***:

5. *For operational feasibility, the backfill should be **emplaceable**, that is to say, exhibit the mechanical qualities that will allow it to be pumped or projected into the gap.*

6. *To achieve the needed industrial performance of the process, in order to be able limit the total time of underground operations to certain duration, on average the backfilling should be able to **proceed at a certain linear pace**.*

   For a grout, this means it must become hard within a certain number of days, after which the casing can be removed and the disposal process continued. For a projected granular material, this means the system must have a sufficient projection capacity, to support a certain linear backfilling speed.

7. *For reasons of operational safety, **dust generation and water run-back** should remain very limited.*

8. *To keep the option of **retrievability** open as much as possible, the strength of the backfill component should be limited.*

   For instance, it could be limited to a compressive strength of less than 10 MPa, in order to allow for a removal of the backfill by use of high-pressure beam technology.

Based on the above described functions and constraints, a set of requirements for the backfill component within the O/N reference disposal concept has been established. Table 2-1 summarizes these requirements and provides more details on the specific criteria that could be applied.

Remarks:

1. The backfill component in the O/N HLW disposal drift concept is not attributed a radionuclide retardation function. Having a high sorption of radionuclides or having a low hydraulic conductivity is not a mandatory requirement for the backfill. Therefore, the backfill component cannot be called a buffer in the true sense of the word. Nevertheless, any of these qualities would be a "nice-to-have".
2. The concern that the backfill component would act as a barrier to gasses generated within its enclosed volume, thus leading to a pressure build-up and a challenge to the mechanical stability of the disposal drift, is considered not to be applicable. It is considered that the gas barrier concern is more limiting for the concrete of the Supercontainer than for the weaker structure of the backfill.
3. It is not a mandatory requirement that the backfill component should have a cementitious high alkaline nature like the concrete buffer of the Supercontainer. Nevertheless, this would be a "nice-to-have", for two reasons:
   a. It would further contribute to the preservation of the high alkaline environment of the overpack established by the Supercontainer,
   b. It would simplify the modeling of the HLW disposal concept, thus making it easier to understand and to communicate to the public and to the regulators.

For these reasons, the backfilling by injection of a specific grout is currently the reference option.

Table 2-1 : Summary of Requirements related to HLW disposal drift backfill in O/N concept

REQUIREMENTS OF BACKFILL MATERIAL IN O/N HLW DISPOSAL CONCEPT		
Description of Objective	**Time Frame of Objective** (magnitude order)	**Associated Material Parameters and Criteria**
FUNCTIONS		
The backfill must: 1. **prevent a cave-in of the disposal drift** 2. in case spent fuel is being disposed, reduce the void space around the Supercontainer, in order to reduce the potentiality for an escape path of the filler material surrounding the spent fuel.	100 000 years	These functions are fulfilled by achieving a virtual 100% filling of the void space within the disposal drift with solid incompressible material.
CONSTRAINTS		
The backfill may not disturb the designed **corrosion**-protective characteristics of the environment around the overpack, created by the Supercontainer. Therefore, the backfill should: 1. not contain aggressive species that are corrosive to iron 2. not degrade the high alkaline nature of the overpack environment	1 000 years (1)	The presence of materials incorporating chlorine (Cl) or susceptible to the release of Cl^- ions, should be very low. The presence of materials incorporating sulfur (S) or susceptible to the release of S^{-2} ions (especially e.g. reduced sulfur species), should be very low. The use of **pozzolanas** in the backfill material is not allowed. Pozzolanas combine with lime in the presence of water to form stable insoluble compounds and thus decrease the pH buffering capacity of the environment around the overpack. Note that the high alkaline nature of the overpack environment would be best ensured by a backfill with a similar nature; i.e. a cementitious material with a pH > 12.5. At the same time, this similarity would simplify the modeling of the disposal concept.
The backfill may not act as a **thermal isolator**. The overpack temperature may not exceed 100°C.	1 000 years (1)	**thermal conductivity** ≥ 1 W/m-°C
The backfill may not disturb the host rock retention characteristics by introducing organic materials that can give rise to the formation of migration-enhancing **complexes** between radionuclides and soluble organic compounds.	1 000 000 years	concentration of the following **organic species**: 1. organic materials **in general**: very low 2. **cellulose-based additives**: not allowed ! 3. **gluconic acid based** compounds: not allowed !
The backfill may not jeopardize the	1 000 years (1)	**thermal expansion** ≤ $10.\ 10^{-6}$ linear per °C

mechanical stability of the disposal drift: 1. by **excessive expansion or shrinkage** with respect to the drift wall 2. by **chemical attack**		**swelling** ≈ 0 (little or none) **chemically inert** with respect to concrete
The backfill should be **emplaceable**, i.e. exhibit the mechanical qualities that will allow it to be pumped or projected into the gap	Operational phase	In case of grout: **fluidity** *<u>criterion</u>: sufficient fluidity to be pumpable over > 30 m and remain sufficient fluidity after pumping to allow mixing for ≥ 5 h (operational objectives for the full-scale mockup test)* In case of granular backfill: **cohesion** *<u>criterion</u>: sufficient cohesion to render a front of emplaced backfill material that has a homogeneous composition and a regularly shaped slope steep enough to allow the projection vehicle to approach and project into the top of the gap.*
On average, the backfilling should be able to **proceed at a certain linear pace**, in order to limit the total time of underground operations	Operational phase	In case of grout: **hardening time** *<u>criterion</u>: time between grout injection and removal of casing ≤ 4 days (current operational objective)* In case of granular backfill: **volumetric projection capacity** *<u>criterion</u>: linear backfilling pace ≥ 1 m/h (current operational objective)*
For operational feasibility and safety, **dust generation and water run-back** should remain very limited	Operational phase	(judgment of the operators)
A constraint associated with the option of **retrievability** is that the backfill should not be too difficult to remove, in order to limit the complexity of an eventual retrieval of the Supercontainer.	100 years	**compressive fracture strength** ≤ 10 MPa (current objective, to allow the use of high pressure beam technology)

(1) more precise indicative values: 800 years in the case of vitrified HLW and 2500 years in the case of spent fuel.

2.2.2 General test objectives

The general objectives of the backfill testing performed in Work Package 4.1 were:

1. Apply, on a 30 m long full-scale mockup, the grout backfill technique developed in Work Package 3 hereby using the same specific grout premix material (but possibly a different W/C ratio). Success is judged on: performance of the injection within a given time frame, (near) complete filing of the annular gap, setting of the grout within the desired time frame, and maintenance of the integrity of the mockup throughout all activities.
2. Evaluate the results in view of a possible application in real repository conditions, hereby considering the aspects of operational performance, logistical needs behind the backfilling operation, operational safety hazards and the mastering of the physico-chemical phenomena.

2.3 Execution of the test

2.3.1 Grout injection procedure

The objective of the experiment is to test the injection technique and to evaluate the results in view of a possible application in real repository conditions. This means that the test has focused on the feasibility of the backfilling technique itself, i.e. the filling of the void. The in-situ limitations have been taken into consideration only where these would clearly impose limiting boundary conditions. An important in-situ limitation concerns the preparation of the grout, i.e. the mixing of the dry premix material with water. It is currently left open which approach will be taken. Options are:

1. grout is prepared in surface installation and is then pumped down to the location to be backfilled through a specific piping system, possibly in one or more steps, involving a buffer tank;
2. grout is prepared in surface installation and is then sent down in one or more mobile tanks to the location to be backfilled, where it is pumped into the void to be backfilled;
3. grout is prepared in the underground, in the vicinity of the void to be backfilled. This seems a less likely option in view of the spatial limitations and the increased operational hazard it entails because more energy-consuming equipment is then applied in underground conditions.

Based on technological considerations (limitation of the involved pressure heads to keep the pump lines of manageable size) the capacity of the concrete pump should be limited to about 20 m^3/h. From the mock-up geometry, it was estimated that about 85 m^3 of grout would have to be injected. Hence, it should be possible to accomplish the injection operation in less than 5 hours time. This conclusion is in line with grout fluidity time requirement postulated in Table 2-1.

For the preparation of the grout in the experiment, initially a procedure involving a buffer tank was considered. One or more concrete mixers would prepare a batch of grout and pour it into the buffer tank, which would serve as the reservoir from which grout would be continuously pumped into the mockup. However, a pre-test on October 18th 2007 indicated that the use of such a buffer tank was a superfluous step and that the batches of grout could be poured directly into the (smaller) reservoir of the concrete pump.

A grout preparation procedure for the test was conceived with 3 mixers of about 10 m^3 each, working in sequence and pouring their batch directly into the reservoir of the concrete pump. A piston-type concrete pump with a capacity of 22 m^3/h was foreseen, although the actually delivered flow rates were expected to be lower. Each mixer is initially filled with 2000 l of water. Then, 20 000 kg of premix material is loaded into the mixer, after which another 500 l of water is added. The premix and the water are then mixed for at least another 3 minutes. The procedure foresees that the quality of the grout in each batch is checked before use. Then, depending on the result, more water can be added to the mixer if necessary.

From experience with the pre-test, a type of big-bag for the premix material was chosen that is not too large (1000 kg) and with a wide bottom nozzle, in order to facilitate the inflow of premix into the mixer. Each big-bag is picked up from the nearby stock and lifted by a polar crane. The big-bag is manually emptied by an operator standing on the mixer. Two polar cranes were deemed necessary for the process. A stock was foreseen of 200 big-bags of premix material, produced and delivered by BASF (see §2.1.2). The photograph of Figure 2-14, which was taken the day of the actual test, shows the configuration with the 3 mixers and the premix being loaded from big-bags. The photograph of Figure 2-15 shows a batch of grout being poured into the reservoir of the concrete pump.

In case of failure, one back-up mixer and one back-up concrete pump of the same capacity were foreseen on site during the test.

Figure 2-14 : Configuration with 3 mixers being with premix material from big-bags

Figure 2-15 : Batch of grout poured into the pump reservoir

2.3.2 Performance of the backfill test with grout (April 8th 2008)

The grout test was executed on April 8th 2008. The test was witnessed on behalf of the EC by Professor Lucie Vandewalle of the KUL University. Due to some problems with the software of the water flow rate measuring system, the loading of the first mixer with premix material could only be started at 10:30 am. It took about three quarters of an hour to load the mixer with 20 000 kg of premix, which was mixed with 2600 l of water. After verification of the grout characteristics, the injection into the mockup was commenced at **12:15 pm**. Figure 2-16 and Figure 2-17 illustrate the on-site verification of the grout characteristics.

Figure 2-16 : Verification of the fluidity of each grout batch

Figure 2-17 : Prisms are cast to verify compressive strength later on

At 13:45 pm it could be observed from the on-line temperature measurements that in section 3 (back-end of the mockup) the grout level had reached the bottom of the steel tube. As more grout arrived inside the mockup, the space under the steel tube got completely full and the grout started to rise into the upper part of the void through the openings in the floor foreseen for that purpose (Figure 2-7). By 15:40 pm, the steel tube was already half-covered. At 17:10 pm, it could be observed from the on-line temperature measurements that in section 3 the top of the steel tube was overflowed. Figure 2-18 and Figure 2-19 show a photograph of the display of the on-line measurements system.

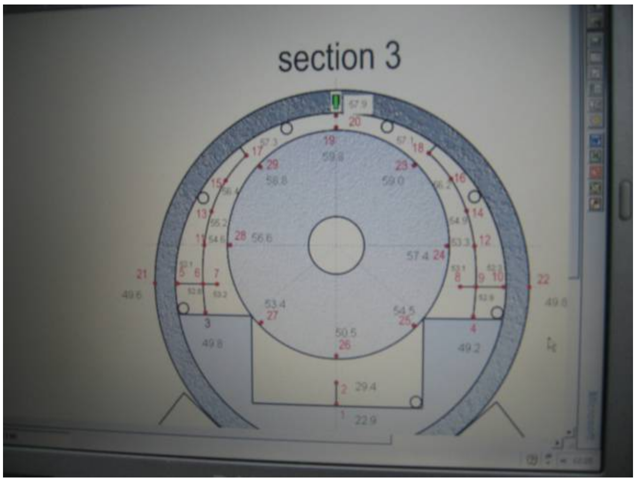


Figure 2-18 : display of the on-line measurement system showing data from cross section 3

Figure 2-19 : display of the on-line measurement system showing axial data from mockup top

At 17:42 pm, fluid was noticed to start flowing from out of the vent (Figure 2-20). At first, this was a small stream, but 2 minutes later, a flow of murky fluid was gushing into the reservoir that was prepared for it (Figure 2-21). The consistency of this fluid was visibly much lighter than the grout being pumped in.

Figure 2-20 : initial flow from the nozzle (at 17:42 pm)

Figure 2-21 : full flow from the vent into the foreseen reservoir (at 17:44 pm)

At **17:48 pm**, the concrete pump suddenly stalled. Afterwards, it became clear that this was due to a lack of fuel in the pump, but this went unnoticed at the time. Immediately, the spare pump was prepared and connected to the mockup. Then, due to some wrong manipulations, the globe valve on the normal injection nozzle got blocked and a spare injection tube had to be used. Finally, at **18:20 pm**, injection could be resumed. Again, murky fluid was gushing from out of the vent. The nature of this fluid did not seem to turn into more grouty material, like it had done in the reduced-scale tests of Work Package 3.

It was decided to stop the injection at **18:30 pm**, to avoid overpressurizing the mockup. Figure 2-22 is a photograph taken at the end of the test. One can observe the injection hose connected to the middle level spare injection nozzle on the left hand side of the mockup. The other hose is connected to the vent nozzle on the top (on the picture held by operator with green helmet).

Figure 2-22 : end of the test (at 18:20 pm)

Table 2-2 provides a summary of the operational data of the test (loading and injection). The average injection flow rate, not accounting for the last batch (nr. 9), throughout the test had been 15.1 m^3/h. Even though this is definitely below the pump capacity (22 m3/h), it is still an acceptable operational average, because it would have resulted in a filling of the void in less than 6 hours. The average injection flow rate was basically determined by the loading process of the mixers with premix material.

In Table 2-3 are the grout characteristics measured on the samples taken from each batch.

Figure 2-23 gives the evolution of the temperatures measured in Section 1 (front end) and Section 3 (back end) of the mockup.

Table 2-2 : Summary of test operational data

Mixer #	Premix contents (kg)	Water contents (liter)	Premix loading time (minutes)	Time of injection start	Duration of injection (minutes)	Injection flow rate (minutes)
1	20 000	2 600	43	12:15 pm	25	24.0
2	20 000	2 600	52	12:44 pm	49	12.2
3	20 000	2 600	43	13:34 pm	45	13.3
4	20 000	2 600	35	14:22 pm	43	13.9
5	20 000	2 600	36	15:07 pm	36	16.6
6	20 000	2 600	39	15:44 pm	35	17.1
7	20 000	2 600	37	16:20 pm	33	18.2
8	20 000	2 600	45	16:54 pm	51	11.7
9	16 000	2 100	37	8 m^3 was prepared, but not fully injected. 3 m^3 is estimated to have been spilt through the vent		

Table 2-3 : Summary of backfill grout characteristics

Mixer #	W/C	Water temperature (°C)	Grout temperature (°C)	Grout fluidity(1) (cm)	Grout air content (%)	Grout viscosity(2) (s)	Compressive strength(3) (MPa)
1	1.300	9.4		68			
2	1.300	9.4	12.1	71	6.1	4.4	
3	1.325	10.4	12.8	69	5.8		1.6
4	1.325	10.4	12.8	71	6.1		
5	1.325	10.4	13.2	72	6.1		1.6
6	1.325	10.4	13.2	73	5.8		
7	1.350	11.0	14.5	73	4.5		2.1
8	1.350	11.0	14.5	70			
9	1.350	11.0	14.5	71	4.8		2.0

(1): fluidity measured as a flow distance in a normalized gutter or "L box" (see Figure 2-16)
(2): viscosity measured as a flow time out of a normalized "V funnel"
(3): compressive strength measured after 20 days

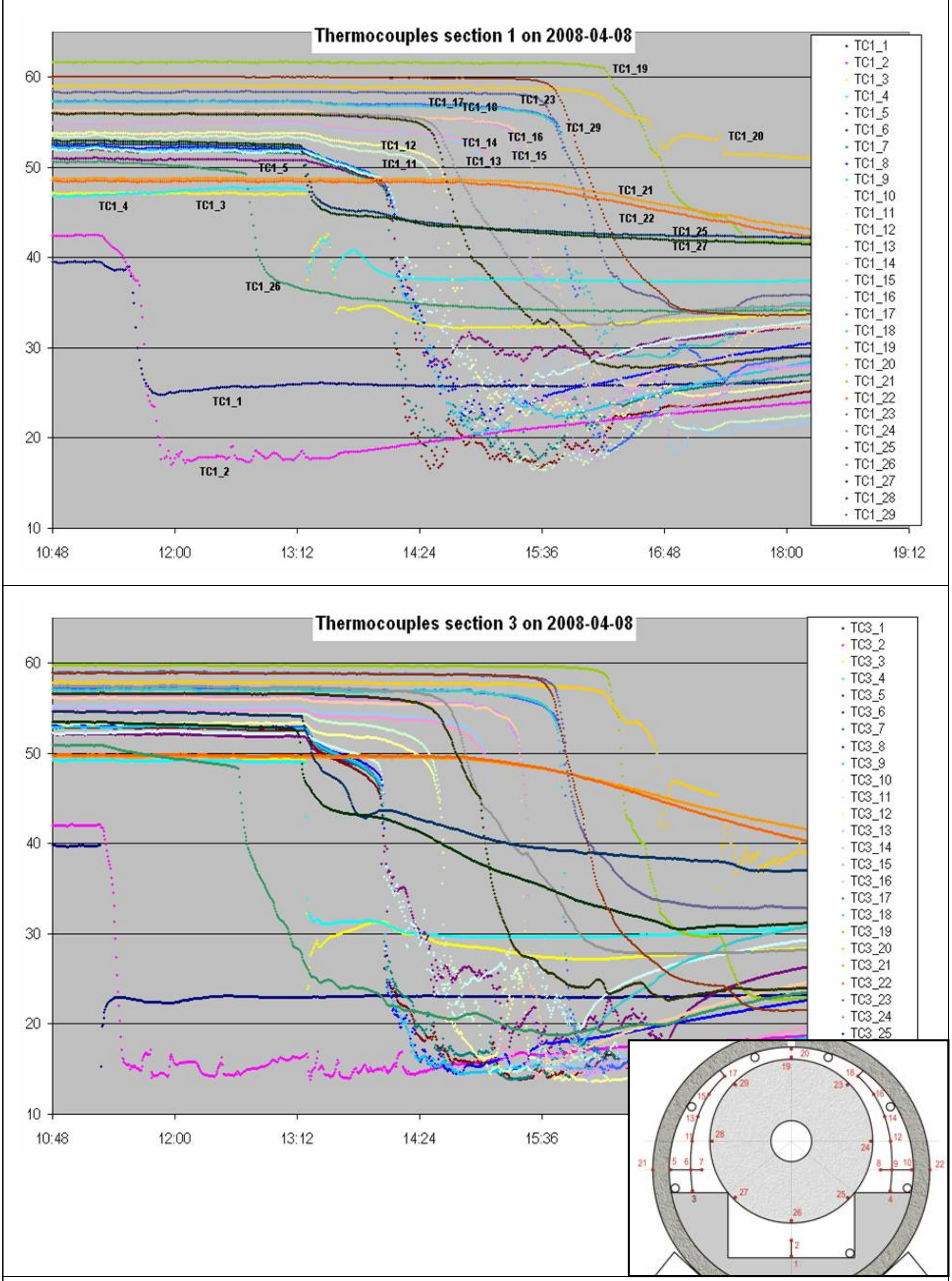


Figure 2-23 : Temperature evolution during the test

2.4 Post-test activities

2.4.1 Continued on-line temperature measurements

The heater inside the mockup was left on semi-automatic control for 2.5 weeks after the injection. It was switched off on April 25th 2008. Another 2 weeks later, around May 7th, the insulation was removed from the mockup. The temperatures in the mockup gradually decreased until, around mid-May, the equilibrium with the surrounding environment temperature was reached.

Figure 2-24 shows the temperatures as measured by the thermocouples in Section 2 (middle of the mockup). The day of the test is marked by the steep decline of all temperatures on April 8th. The switch-off of the heater is marked by the temperature peak around April 25th.

As already known from the reduced-scale tests of Work Package 3, there is no visible effect of the cement hydration heat.

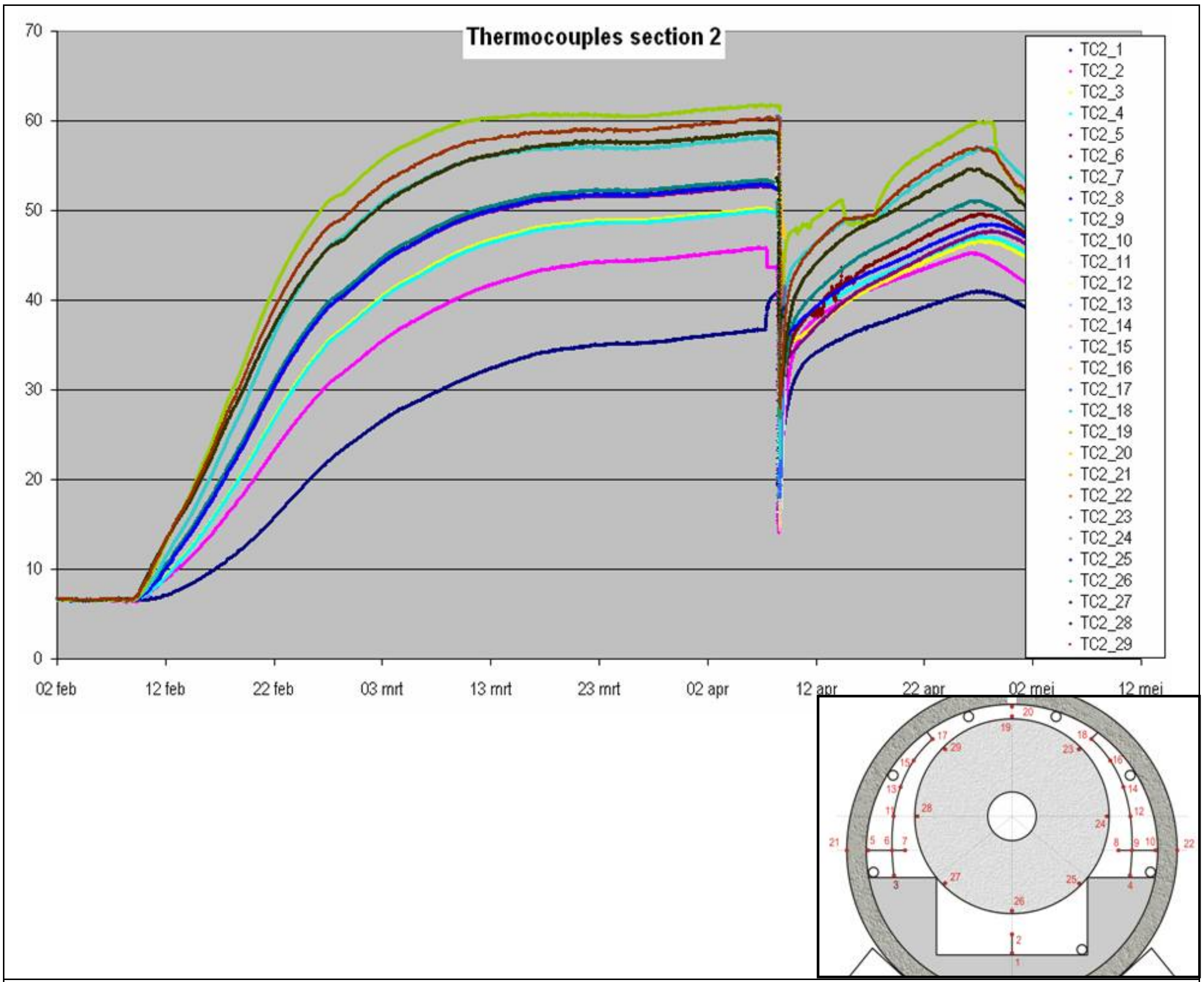


Figure 2-24 : On-line temperature measurements before, during and after the test

2.4.2 Visual inspections from the top of the mockup

One week after the test, the instrumentation holes at the top of the mockup were opened and it was observed that there was a pocket of water residing at the top of the annular gap. The water, some 900 l (or about 1% of the total void volume), was removed with a siphon.

Visual inspections through the instrumentation holes after the letdown of the water pocket revealed that the space taken by this pocket ranged from 1 cm at the back of the mockup to 5 cm at the front (Figure 2-25). This finding was an indication that the protrusion of the injection tube to the back of the void had led to an inclination of the grout level, which was exactly the purpose of this long protrusion. Note that already during the test, the on-line measurement system had indicated that the grout was filling the void in a continuous wave propagating from the back to the front of the mockup. Compare in Figure 2-23 the time of the temperature drop (an indication that the grout has reached the sensor) of a certain sensor in Section 3 with the corresponding sensor in Section 1.

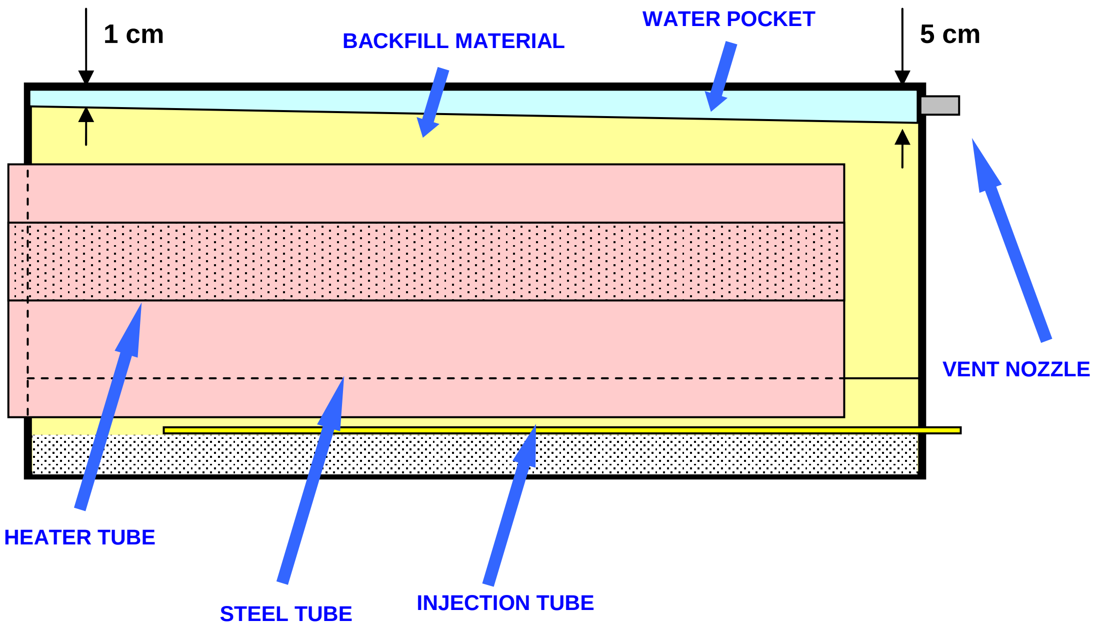


Figure 2-25 : Location of the residual 900 l water pocket

2.4.3 Borehole drilling and sampling (following the nature of the backfill)

When the instrumentation holes at the top of the mockup were opened one week after the test, it was first found that the grout was not becoming hard the way it had done in the reduced-scale tests of Work Package 3. The backfill resulting from the grout had the physical nature of a paste.

Later on, small borehole samples (only a few centimeters in diameter) were taken from the side of the mockup. These revealed the same paste-like nature of the backfill.

Also the strain gauges, of which four were installed in each of the three Sections, did not give any indication that the backfill was becoming hard in the weeks and even months after the test. Note that grout setting is typically indicated by a strain gauge by distinct negative elongation. This is not visible in Figure 2-26; the negative elongation that can be seen is purely a temperature effect (the general cooldown of the mockup).

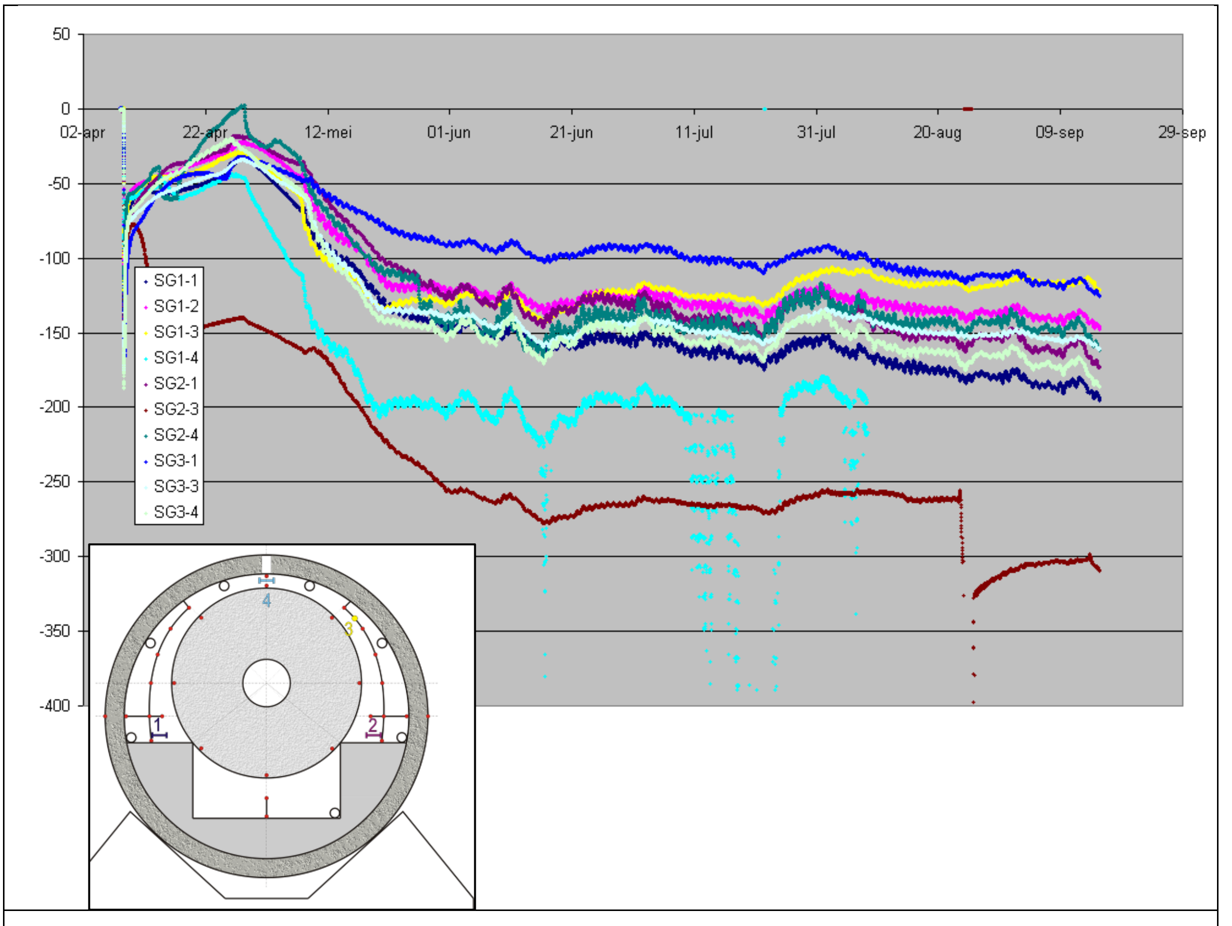


Figure 2-26 : On-line strain measurements inside the backfill (elongation expressed in 10^{-6})

In September, small boreholes drilled through the back-end lid confirmed the fact that the backfill was still paste-like. On the other hand, it also provided some reassurance that it would not be dangerous to remove one of the lids. In October, the back-end lid was removed. The backfill face in contact with the open air became hard relatively fast, but a borehole drill made two weeks later revealed that 20 cm deep into the face, the backfill was still very much paste-like. It is noteworthy to mention that after the removal of the lid the backfill face did not shown any signs of sloughing, even though it was unsupported. There was no sign of any water seepage from out of the backfill either. The backfill face does not show visual signs of inhomogeneity. Depending on the evolution of the hardening of the grout, plans can be made for making a slice-cut of the mockup, like it was done with the reduced-scale mockup for grout.

Figure 2-27, Figure 2-28 and Figure 2-29 provide a view of the backfill face after removal of the lid. Notice that the backfill material has filled up the annular gap to the top.

The TDR sensors did not give meaningful results, most probably due to the slow (if any) setting of the grout. The actual measurements showed a high loss of the electro-magnetic energy in the pulse, such that no reflected pulse could be detected. New attempts will be performed in 2009. Thermal conductivity measurements are also planned for 2009. During the heated phase, no accurate measurements were possible as a very stable temperature is required for the measurement.

O/N and EURIDICE intend to document the full-scale mockup test with a video of about 10 minutes. Production of this video will probably for in 2009.

Figure 2-27 : Back-end side of the mockup after removal of the lid (picture taken December 2nd 2008)

Figure 2-28 : Close-up of the flat front of already hard backfill material

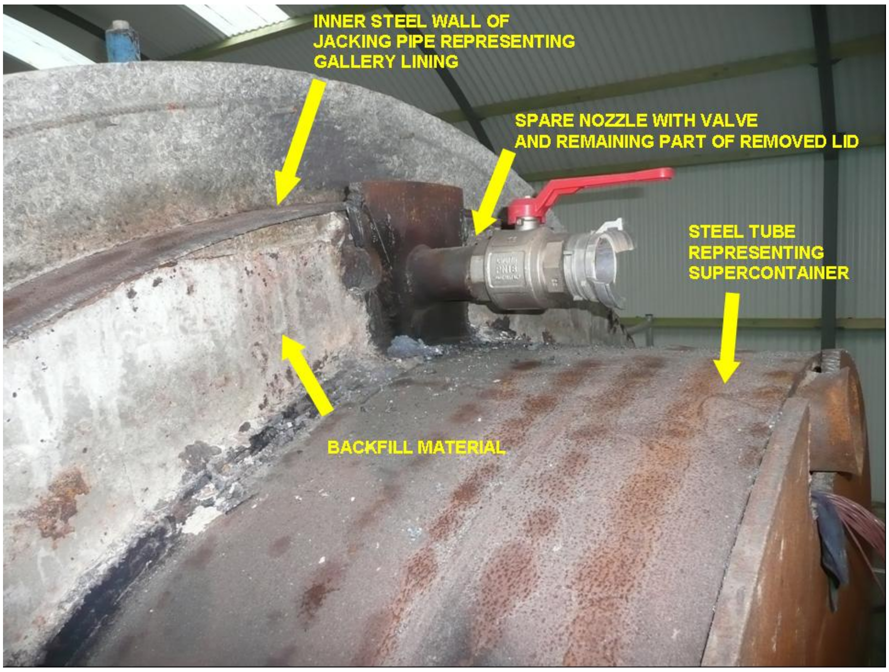


Figure 2-29 : Close-up of the top of the backfilled annular gap

2.5 Analysis of test results and conclusions

2.5.1 Level of success of the test

The general test objectives, defined in Section 2.2.2, were:

1. Apply, on a 30 m long full-scale mockup, the grout backfill technique developed in Work Package 3 hereby using the same specific grout premix material (but possibly a different W/C ratio). Success is judged on:
    a. performance of the injection within a given time frame
    b. (near) complete filing of the annular gap
    c. setting of the grout within the desired time frame
    d. maintenance of the integrity of the mockup throughout all activities
2. Evaluate the results in view of a possible application in real repository conditions, hereby considering the aspects of :
    a. operational performance
    b. logistical needs behind the backfilling operation
    c. operational safety hazards
    d. physico-chemical phenomena inside the mockup

Concerning the first objective, it can be concluded that **the application of the technique was essentially successful, but not fully**. The injection was performed at a satisfactory rate, the annular gap was as good as completely filled and the mockup design proved to be very robust. The grout did however fail to become hard as it should. These conclusions are elaborated here below:

- The annular void was filled within the operational time limits. The injection started at 12:15 pm and ended at 18:30 pm, but the 30 minutes of stand-still because of the concrete pump failure should not be taken into account. So, the injection was performed in 5 ¾ hours. Although the average injection rate was somewhat lower than originally expected, the result is still acceptable; 5 ¾ hours is a time frame during which a manufacturer can generally guarantee the fluidity of his product.

- The annular gap inside the mockup was 99% backfilled. The same technique was used whereby the grout is injected at the bottom and consequently rises up to the top of the void. The same grout premix was used, with a similar W/C (ranging from 1.3 to 1.35, where in the reduced-scale test it was 1.34). The protrusion of the injection tube up to 85% of the section length resulted in achieving a back-to-front wave propagation of the grout level, thus driving out the remaining air in the gap through the vent nozzle in the front lid.

- The mockup withstood the stresses from the thermal and mechanical load cycles without any visible problem. Thermal loading came from the sequence of initial heatup, sudden cooldown during the injection, consequent slow heatup, and then gradual cooldown after the switch-off of the heater. The mechanical loading came from the static and dynamic pressure differences invoked by the grout.

- The backfill grout failed to become hard in a matter of days, as it should do in the real life repository (see the associated requirement in §2.2.1). As a matter of fact, at present, many months after the injection, the material is still not really hard. When the back-end lid of the mockup was removed it become hard only locally. One can deduct that, without any openings in the mockup through which some water can evaporate to the open air, the material probably would remain ductile for an indefinitely long period of time. This is an important difference with the reduced-scale test of Work Package 3, where the grout did set in a matter of days.

Concerning the second objective, it can be concluded that **the test was largely successful in providing a broad information basis which can be used for the next phases in the development of the grout backfill technology**. The test allowed to monitor and analyze, on a 1/1 scale, the thermo-mechanical dynamics of the grout injection process, the actions performed by the operators and the involved operational safety hazards. Also, it gave a better insight in the logistical needs behind the backfill operation. A plausible explanation for the failure of the grout to become hard was derived and a remedy was proposed. On the other hand, it is not certain whether segregation of the grout inside the mockup has taken place. These conclusions are elaborated here below:

a. In line with recommendations after the reduced-scale test in Work Package 3, the full-scale mockup was extensively equipped with measurement devices. A large amount of on-line data was gathered on the temperature evolution inside the mockup before, during and after the injection. This allowed analyzing the thermal behavior of the mockup as well as a precise monitoring of the filling of the annular void during injection. The ultrasonic level sensors managed to some extent to capture the grout level as it was rising above the top of the steel tube, although about half of the sensors apparently were malfunctioning and/or the phenomena at the top of the mockup at the end of the injection were too dynamic for the sensors to be captured well. The strain gauges meant to detect the setting of the grout were functioning well, but unfortunately the grout did not set. On the operators side, all actions were filmed, photographed and times were recorded. Two operational problems occurred (the loss of the pump and the blocking of the valve on the main injection nozzle), but these could be overcome without losing much time. The reserve pump was connected to a reserve injection point fairly rapidly. The spilling of a certain quantity of fluid out of the vent nozzle towards the end of the test should be regarded as normal and a reservoir should be foreseen. This was the case in the test, but the quantity of fluid (about 3 m^3) was so large that it did overflow the reservoir. Such a large volume should not be regarded as normal. It is however the result of a physico-chemical phenomenon that should be resolved in the next phases in the development of the grout backfill technology (see discussion here below).

b. The logistical needs, i.e. the boundary conditions for the injection workspace, were adequately fulfilled. The 3 mixers and 2 polar cranes were able to sustain a sufficient average injection rate of 15 m^3/h. Fulfilling the logistical needs proved to be an important challenge during the preparatory phase of the test, absorbing much time and effort. It made those involved aware that next to the demonstration of the backfilling technique itself, also the provision of the flow of backfill material to the places in the repository where it is needed will require a dedicated design and demonstration program. Moreover, this design will need to be compliant with the operational management concept of the repository. Therefore, several backfill options should be investigated.

c. A main operational safety hazard is the rupture of the casing during the injection phase, as a result of which the workers would be flooded with grout. Since at no time during the test activities the physical integrity of the mockup was challenged, the design bases for the lids, nozzles and valves can be used as a starting point for the design of the real-life backfill equipment. As a remark; the fact that the risk involved with this type of accident is proportional to the length of the section of gallery to be backfilled is an argument for limiting the length of the section in the operational procedure.

   Lower level operational safety hazards are the more conventional ones:

   - radiological operational safety hazards, coming from the fact that operators are working in the proximity of the Supercontainer. The working procedures should take account of the applicable legislation and take the ALARA principle into account.
   - Non-radiological operational safety hazards coming from manipulation of heavy weights (e.g. the pump) or rupture of pressurized hoses, but these concerns are part of the conventional domain of operational safety, which is covered by the applicable legislation. The fact that the backfill operation has to be performed in underground conditions appeals to the applicable mining safety rules.

d. Two particular physico-chemical phenomena inside the mockup have been the subject of investigation after the test: the setting of the grout and the eventual segregation of the grout. A summary of the results of these investigations are given here below:

   - The grout ultimately failed to become hard. This is an important difference with the reduced-scale test of Work Package 3, where the grout became hard in a matter of days, as it should do in the real-life repository. After reviewing the possible causes of this difference (involving consultation of the known concrete expert prof. Glasser of the Aberdeen University), the only plausible explanation seems to be that the 1.3 to 1.35 W/C ratio of the used grout is a critical value. Above this value, there is too much water so that the cement granules reacting with water are not able to join and create a rigid spatial network. The hypothesis is that in the reduced-scale test, a certain quantity of water was absorbed by the concrete of the standard pipes representing the gallery wall and that thus the critical W/C was undershot. In the full-scale test, because of the inner steel wall of the concrete jacking pipes, no water was able to escape and the W/C remained above the critical value. One can counter argue that in the reduced-scale test, the concrete of the pipes had been saturated by the preceding watertightness test. However, it was not measured at the time what the exact degree of saturation of these pipes was, so it could have been less than 100%. In the real-life repository, the gallery lining will also be saturated up to a certain degree and thus unlikely be able to absorb much water. So, the full-scale test has in any case been conservative with respect to this phenomenon.
   - It is possible that there has been some segregation of the grout inside the mockup. One indication of this hypothesis is the observation of the large quantity and the much lighter consistency of the fluid that was spilling from the vent nozzle at the end of the test. Another indication is the residing 900 l pocket of water that was observed after the test. These observations can be explained by assuming that there was some segregation of the grout inside the mockup. If the sand is assumed to have segregated to some extent from the mixture, the resulting lighter fluid (containing more cement and less sand) would have the tendency to float on top of the heavier mixture and thus the consistency of the fluid spilling from out of the nozzle would be explained. It would also explain its large quantity, because this can not come from water remaining after the mockup watertightness test alone. It would also explain the residing 900 l of water, which could have been created after the test by precipitation of the cement from the then stagnant lighter fluid. Nevertheless, although it could explain the cited observation, the segregation hypothesis is not proven.
   - The most straightforward way to resolve the grout setting problem is to decrease the W/C ratio. The BASF experts have suggested limiting the W/C to a value of maximum 1.25, and this depending on the type of concrete pump. A piston-type pump (like used in the full-scale test) brings along a higher segregation risk than a screw-type pump (like used in the reduced-scale test of Work Package 3. This will result in a higher but still relatively low compressive strength of the backfill (10 MPa or more is estimated). The fluidity of the grout can be maintained at an adequate level by augmenting the superplasticizer content in the premix. The used polycarboxylate ether-based superplasticizer can probably be employed in larger quantities than estimated up to now without impacting the radionuclide retardation performance of the repository system. It is possible that by decreasing the W/C, the segregation issue will be resolved together with the grout setting problem. This remains to be seen. It should however not impair the search for the cause of the observed phenomenon.

2.5.2 Opportunities for the future

The next phases in the development of the grout backfill technology can use the information basis provided by the work within ESDRED. The research should be continued taking a lower W/C (maximum 1.25) and a premix with a higher superplasticizer content as a starting basis.

Further research should be coupled with an investigation in to the logistical needs behind the backfill operation, involving a dedicated design and demonstration program. Since in its turn the backfill logistics is coupled with the operational management concept of the repository, it is recommended to investigate several options.

Possible options are:

1. grout is prepared in surface installation and is then pumped down to the location to be backfilled through a specific piping system, possibly in one or more steps, involving a buffer tank;
2. grout is prepared in surface installation and is then sent down in one or more mobile tanks to the location to be backfilled, where it is pumped into the void to be backfilled;
3. grout is prepared in the underground, in the vicinity of the void to be backfilled. This seems a less likely option in view of the spatial limitations and the increased operational hazard it entails because more energy-consuming equipment is then applied in underground conditions

Also the use of a dry granular backfill material (tested in Work Package 3) should not be forgotten as a possible way forward. It may offer a number of advantages that the grout injection technique does not have, e.g. the rupture of the vessel, duct or hose in which the backfill material is transported has potentially less far-reaching consequences in the case of a dry granular material compared to a grout.

3 IN-SITU SEAL PERFORMANCE TEST (BY GRS)

3.1 Background (of the SB experiment)

In 1998, the German government expressed doubts with respect to the suitability of salt to host a nuclear repository. All exploration activities at the Gorleben site were halted by the end of 2000 and a moratorium was imposed for three to ten years. During this time all pending issues shall be looked into, and new formation-independent site selection criteria are to be developed in order to identify alternative sites and host rocks with favourable geological settings. To support the development of formation-independent criteria, clay/claystone formations are increasingly considered in the German R&D programme in addition to salt. In 2000, GRS intensified investigations to test the suitability of clay/sand mixtures as a sealing material in a clay repository, especially for the safe closing of repository rooms containing gas generating waste.

In contrast to highly compacted buffers, clay/sand mixtures exhibit a high permeability to gas in the unsaturated state and a comparably low gas entry/break-through pressure in the saturated state while providing an adequate self-sealing potential due to swelling of the clay minerals after water uptake from the host rock. By using optimised material mixtures, the evolution of high gas pressure in the repository near-field due to corrosion of the waste containers will be avoided and possible migration of radionuclides from the waste matrix in the liquid phase through the buffer will be diffusion controlled just like in the host rock.

In a clay repository, this *granular sealing material may be used as buffer and/or as sealing backfill* in disposal boreholes or disposal drifts containing either Nuclear Spent Fuel (NSF) or vitrified high-level waste (HLW), as illustrated in Figure 3-1. The buffer/backfill material will be installed in drifts or boreholes as a slightly compacted embankment.

A key step in the development of this buffer/backfill material is the SB experiment performed at the GRS laboratory in Braunschweig and at the Mont Terri Rock Laboratory (MTRL) in Switzerland.

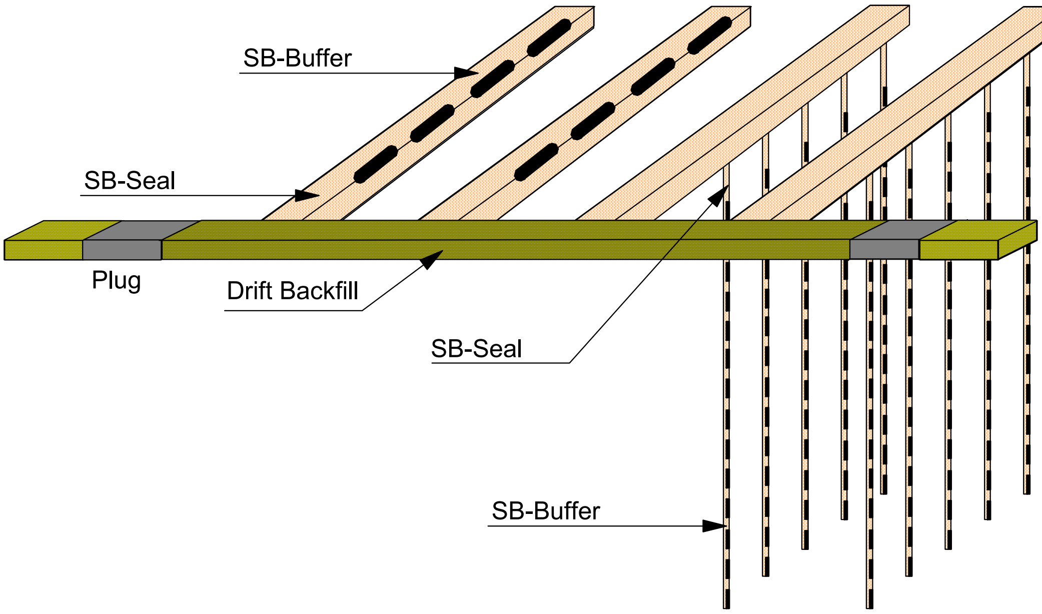


Figure 3-1: SB-buffer and seal in HLW disposal drifts and boreholes

3.2 Test installation and used seal materials

3.2.1 Seal materials

The extraordinary sealing properties of clay/sand mixtures have first been investigated in detail in the geotechnical laboratory of GRS within two preceding projects, the “2-Phase Flow” [1] and the KENTON project [2]. Seal properties such as permeability to water and gas, gas break-through pressure, and swelling pressure have been determined for different mixing ratios and different degrees of compaction in order to provide a data basis for the envisaged further large-scale laboratory mock-up and in-situ tests.

The investigations of the “2-Phase Flow” and the KENTON projects have shown that the single-phase permeability to gas was not significantly dependent on the clay content. The gas permeability for the samples with 10 % clay and 25 % clay ranged between 1.3E-13 and 3.8E-13 m^2. At 50 % clay content the gas permeability was slightly higher and amounted to between 2.3E-13 and 1.2E-12 m^2. In contrast to that, the clay content clearly affected the single-phase permeability to water. The measured water permeability was between 2.9E-13 and 5.3E-13 m^2 (for 10 % clay), between 1.2E-16 and 5.3E-15 m^2 (for 25 % clay), and below 1E-22 m^2 for the 50 % clay samples. The gas break-through pressures varied for the 10 % and 25 % clay samples from 0.02 to 0.05 MPa. For samples with 50 % clay a break-through was determined only in one case. The measured correspondent gas break-through pressure was 0.05 MPa.

The results of the aforementioned investigations are summarized in Table 3-1.

Table 3-1 : Parameters of “2-Phase Flow” and “KENTON” samples

Sample	Grain density	Bulk density	Porosity	Gas permeability	Water permeability	Gas break-through pressure
Clay/sand-ratio	ρ_g	ρ_b	Φ	k_g	k_w	p_{bth}
	g/cm³	g/cm³	%	m²	m²	MPa
10/90	2.62	2.073	20.9	2.80E-13	1.60E-15	0.03-0.05
25/75	2.59	2.061	20.4	1.80E-13	1.30E-18	0.05-0.2
50/50	2.540	1.954	23.1	4E-13	<1E-22	n.d.

In the compacted state, the mixtures with lower clay content were found suitable to fulfil the material properties described in section 3.1. Considering the influence of installation density on the hydraulic behaviours when being emplaced as a slightly compacted embankment (like in a repository), the demanded properties may have to be improved by a higher clay content. For this reason, the laboratory investigations for the selection of optimised material mixtures within the SB experiment were performed on mixtures with clay contents of 35 %, 50 % and 70 %.

The seal material consists of bentonite powder (Calcigel) and ordinary sand. The grain density of the sand used in the laboratory is 2.65 g/cm^3, and the grain density of the Calcigel is 2.491 g/cm^3.

The most important material properties as criteria are the installation density and the porosity, respectively, the water permeability, the gas break-through pressure, and the gas permeability after break-through.

Installation density and porosity

First, the installation densities of the sealing materials were investigated on small samples in an oedometer cell with a diameter of 50 mm. In this case sample preparation was made by mixing and compaction by hand. To optimise the preparation procedure, clay and sand were mixed together in an electric mixer and installed in a tube with a diameter of about 290 mm, similar to that of the planned boreholes. In this case the material was emplaced in a plexiglass® tube by layers and compacted by a vibrator. According to the installed mass and volume of the material, the installation density was determined.

From the results, the other state parameters of the compacted material such as grain density, water content and porosity were determined. The grain density of the grinded material was determined with helium using an air comparison pycnometer after Beckman. The results are summarized in Table 3-2 and Table 3-3.

Table 3-2 : Achieved installation densities for the case of hand- compaction

Sample	Grain density (dry)	Grain density (state of delivery	Bulk density (dry)	Bulk density (state of delivery)	Porosity (dry)	Porosity (state of delivery)
Clay/sand ratio	ρ_g	ρ_g	ρ_{bd}	ρ_b	Φ_d	Φ
	g/cm³	g/cm³	g/cm³	g/cm³	%	%
35/65	2.672	2.578	1.816	1.869	32.0	27.5
50/50	2.676	2.572	1.756	1.821	34.4	29.2
70/30	2.696 *	2.573	1.603	1.680	40.5	34.7
Calcigel	2.706	2.491	n.d.	n.d.	n.d.	n.d.
Sand	2.672	2.65	n.d.	n.d.	n.d.	n.d.

* calculated by the grain densities of the pure sand and Calcigel

Table 3-3 : Achieved installation densities for the case of vibrator-compaction

Sample	Grain density (dry)	Grain density (state of delivery	Bulk density (dry)	Bulk density (state of delivery)	Porosity (dry)	Porosity (state of delivery)
Clay/sand ratio	ρ_g	ρ_g	ρ_b	ρ_b	Φ	Φ
	g/cm³	g/cm³	g/cm³	g/cm³	%	%
35/65	2.672	2.578	1.876	1.930	29.8	25.1
50/50	2.676	2.572	1.668	1.73	37.7	32.7
70/30	2.696*	2.573	1.394	1.461	48.0	42.4
Calcigel	2.706	2.491	n.d.	n.d.	n.d.	n.d.
Sand	2.672	2.65	n.d.	n.d.	n.d.	n.d.

* calculated by the grain densities of the pure sand and Calcigel

Permeability, gas break-through pressure, and swelling pressure

For the determination of the hydraulic parameters, the clay/sand mixtures were again installed in the oedometer cells as well. The installation densities corresponded to the densities described above. The water contents of the materials were determined by drying in an oven according to DIN 18121-1.

The gas permeabilities were measured under the installed conditions of the sealing material compacted by hand. After the measurement of the gas permeability, the samples were saturated with Opalinus clay solution

[3] and the swelling pressure as well as the water permeability was determined. For the measurement of the gas break–through pressure, gas was injected by increasing the gas pressure applied to the saturated samples.

Saturation

All investigations on saturation were performed on samples compacted by hand. In a first group of the tests, samples were saturated with Opalinus clay solution at atmospheric pressure, only.

The investigations showed, that saturation increases somewhat with increasing clay content. Furthermore, a dependence on time of the distribution of the saturation along the samples was observed. It is trivial that highest saturations were measured near the contact of the water with the samples.

In a second group, samples with a clay/sand ratio of 35/65 and 50/50 were saturated with Opalinus Clay solution at an increased injection pressures of 1 MPa. The measurements were performed to investigate the influence of pressure on the saturation process and to determine the water permeability as well as the gas break-through pressure. After saturation, the measured water permeability (for the Opalinus Clay solution) showed that the permeability of the samples with the lower clay content of 35 % was somewhat higher than the permeability with the clay content of 50 %.

The investigations of the gas break-through pressure were performed with clay/sand samples 35/65 and 50/50. The gas was injected by the displacement of the gas from a bottle by water at constant flow rate. The constant flow rate of the water was controlled by a HPLC-pump. Due to the capillary entry pressure, the gas injection pressure increased up to the point of gas break-through (gas break-through pressure). At this state, a gas flow through the samples was given.

After gas break-through, the gas permeability was measured and the corresponding water content for one sample of both clay/sand mixtures was determined. Due to the higher clay content, a lower permeability of the samples 50/50 was measured. The remaining water content of the 35/65 clay/sand mixture was 16 % and that of the 50/50 clay/sand mixture was 21.4 %. The higher water content of the samples 50/50 can be explained by a better absorption of water due to the higher clay content.

Table 3-4 summarizes ranges and mean values (in parentheses) of the determined properties for the investigated clay/sand mixtures and compares them to the requirements described in Section 3.3.1. It is obvious that the 35clay/65sand and 50clay/50sand mixtures meet the requirements completely and they have thus been selected for further mock-up and in-situ testing.

It can be expected that the gas break-through pressure may reduce further in the case of significantly lower gas generation rates which are to be considered in a real repository. The extrapolation of the test results to mixtures with clay contents less than 50 % suggests that the 70clay/30sand mixture may have higher swelling pressure and gas break-through pressure than the given upper limit.

3.2.2 Test installations

As mentioned above, proper installation techniques assuring the required installation densities are extremely important for the successful conduction of the in-situ experiments. In addition, the saturation time of the seal is to be considered in the design of the in-situ experiments. Before going in situ, both, the installation technique and the saturation time were to be tested and investigated for different material mixtures in large-scale mock up tests in the GRS surface laboratories at Braunschweig, respectively.

Table 3-4 : Comparison of measured parameters to requirements (averages in parentheses)

Measured parameters at installation conditions					
Sample	Gas permeability under dry conditions	Initial water permeability at full saturation	Gas break-through pressure	Gas permeability after gas break-through	Swelling pressure
	m^2	m^2	MPa	m^2	MPa
35/65	1.2E-13	3.3E-17 - 9E-18 (5.2E-18)	0.4 - 1.1 (0.75)	1.1E-17 - 1.6E-17 (1.4E-17)	0.2 - 0.4 (0.28)
50/50	7.5E-14	1.1E-18 - 4.3E-18 (2.2E-18)	0.4 - 2.8 (1.83)	5.5E-18 - 6.2E-18 (5,9E-18)	0.3 - 0.5 (0.35)
70/30	1.2E-15	5.5E-19	1	n.d.	0.4-?
Requirements					
	Gas permeability under dry conditions	Initial water permeability at full saturation	Gas break-through pressure	Gas permeability after gas break-through	Swelling pressure
	high	1E-17 - 1E-18	2	high	2

Mock-up Tests

The mock-up tests are performed in vertically arranged steel tubes and they are designed as a full-scale replica of the envisaged in the in-situ experiments (Figure 3-4). The lower fluid injection volume is filled with a porous material (stone chips or sand). At top of the porous medium a filter frit is placed for ensuring a homogeneous distribution of the injected water over the entire borehole cross section. Above the filter frit, the clay/sand-seal is installed in several layers to a height of 1 m. The predetermined installation density of about 1.9 g/cm^3 for the 35/65 clay/sand mixture has been realized by using an electric vibrator for material compaction. A further filter frit is installed above the seal for water and gas collection. The whole test set-up is sealed against the ambient atmosphere by a gastight packer on top of the upper filter frit. In contrast to the in-situ experiments where instruments are not installed in the SB seal itself to avoid any negative impact on the sealing properties, the mock-up is equipped with sensors in the test tube wall to monitor the pore and total pressure evolution at three levels along the seal. Additionally, two total pressure sensors are installed at the bottom of the upper frit. Furthermore, each mock-up is equipped at the inlet and the outlet with some pressure and flow sensors to enable determination of the material permeability to gas and water as well as the gas break-through pressure and the remaining permeability to gas after gas break-through. Figure 3-2 shows the principle layout of a SB mock-up and Figure 3-3 shows the installation of the packer in the mock-up in GRS's laboratory in Braunschweig.

In-situ experiments

This work package is conducted in the SB test field, a niche of 5 m width, 4 m height and 8 m length in the MTRL. Four vertical boreholes of 0.31 m diameter were drilled in the test room floor to a depth of 3 m (Figure 3-4). Three boreholes have been sealed with the selected clay/sand-mixtures and the fourth borehole has been sealed with a granulate of pure bentonite provided by NAGRA for observing its seal function in comparison to that of the clay/sand mixtures.

All experiments are designed in principle the same way as the mock-up experiments. However, because of the long saturation times experienced in the mock-up tests (see section 3.4.1 below) the seal length was reduced from 1 m to 0.5 m in case of the experiments using the 50/50 clay/sand seal and the 100/0 pure bentonite seal. Instruments for measuring different hydro-mechanical parameters have been installed as well. No instruments have been installed in the SB seal itself to avoid any negative impact on the sealing properties.

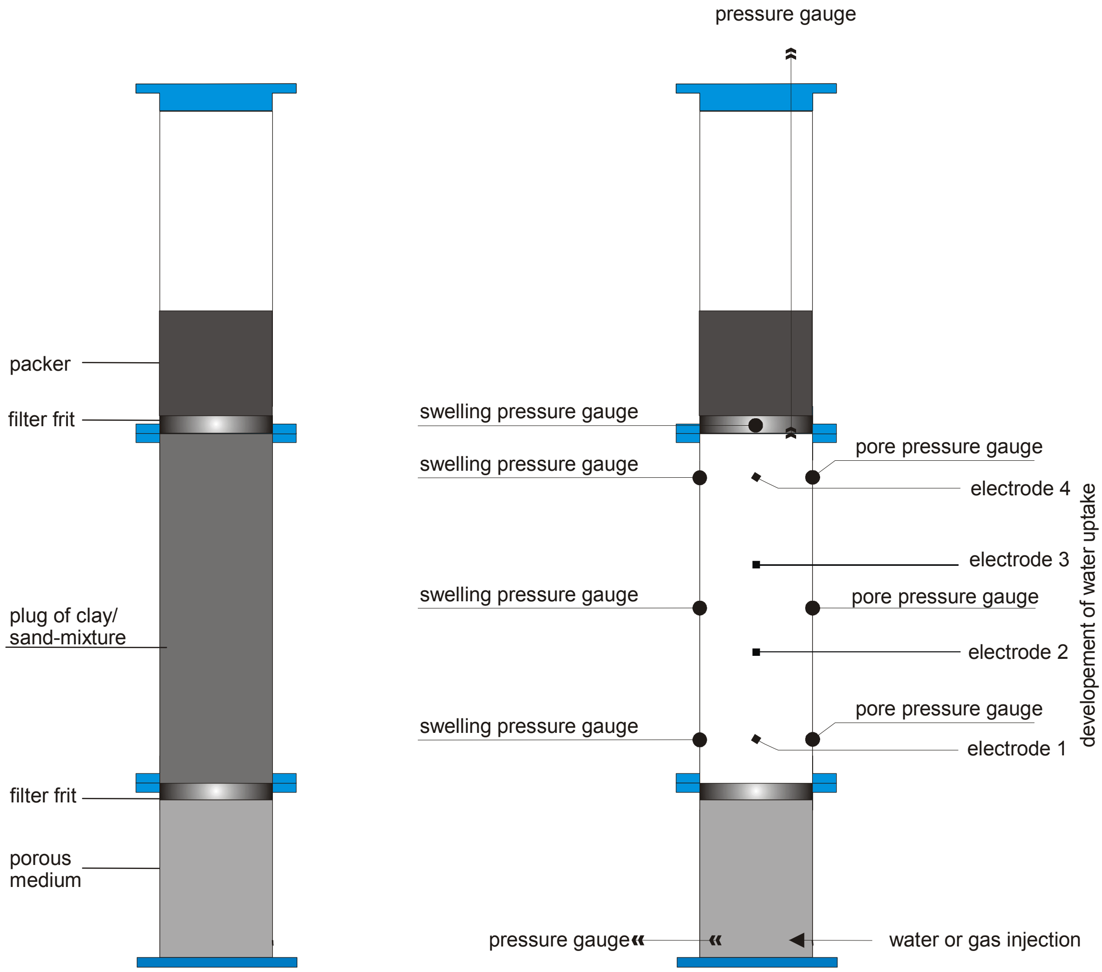


Figure 3-2: Principle layout of test tubes type 1 with the locations of possible measuring sensors

Figure 3-3: Photo of Mock-up 2 at the GRS laboratory in Braunschweig/Germany

Figure 3-4 shows the layout of the test niche and the principle design of one of the borehole sealing experiments. In situ, the most upper part of the test borehole is grouted for keeping the packer in place at possibly higher swelling pressures of the SB seals.

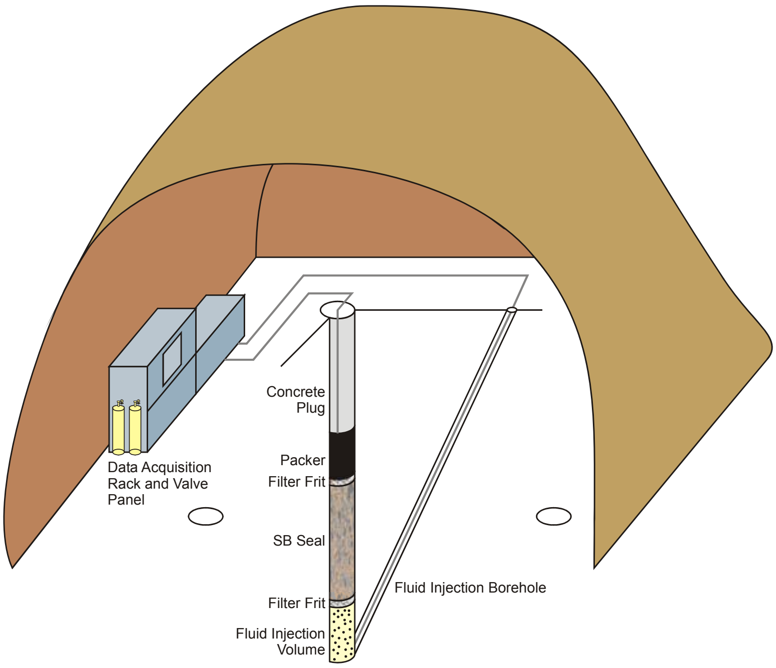


Figure 3-4 : Principle design of a SB-borehole sealing test

For saturation or de-saturation of the seal water or gas is injected through an injection tube running from a valve panel in the test room via an inclined borehole into the lower injection volume. The water or gas flowing through the seal is collected in the upper filter frit by a further tube running back to the control valve panel where gas and water flow rates and pressures are controlled and measured.

The in-situ experiments have been taken into operation sequentially since October 2005.

Design calculations

As a first step of the test design activities, scoping calculations were performed to assess the time needed to reach full saturation in the mock-up and in-situ experiments [4]. The calculations were performed with CODE_BRIGHT on basis of the material data determined in the laboratory investigations and data taken from the literature.

According to the results of the scoping calculations the saturation time determined for the 35/65 clay/sand mixture amounts to about 170 days for the mock-up tests and 300 days for the in-situ experiment and for a 50/50 clay/sand-mixture 570 days for the mock-up and 1050 days for the in-situ experiment for a seal length of 1 m and a water injection pressure of 1 MPa. As the time period of 1050 days predicted for the 50/50 seal was considered a too long period of time it was decided to reduce the length of the 50/50 and the 100/0 clay/sand seals 1 m to 0.5 m in the in-situ experiments. In this case it could be expected that the seal saturation will be reached after a reasonable period of time, which is only slightly longer than that predicted for a 35/65 clay/sand seal.

3.3 Objectives of the test

3.3.1 Requirements for the seal material

The most important material properties the used seal materials should meet in a repository are listed in the following:

Permeability to gas and diffusivity

The buffer should have a high permeability to gas. One way to avoid the development of a high gas pressure in the disposal rooms is to allow the generated gases to migrate through the seal. Right after material installation, the permeability to gas in the unsaturated state ranges between 1.E-13 and 1.E-15 m^2. According to preliminary lab investigations, it remains above 1.E-17 m^2 after gas break-through in the saturated state.

Permeability to water

The buffer should have a low permeability to water. After water uptake from the host rock, the water permeability of the material reduces because of the swelling of the clay minerals. An initial value of about 1.E-17 and 1.E-18 m^2 would be sufficient in analogy to the permeability of 1.E-14 and 1.E-16 m^2 of the excavation disturbed zone (EDZ) in the host rock [5]. It is expected that the permeability to water will reduce further as a result of ongoing rock creep with healing of the EDZ and compaction of the sealing material.

Gas break-through pressure

As the seal is designed to act as a gas vent the gas entry/break-through pressure of the sealing material must be low enough in comparison to the gas entry pressure of the host rock to ensure gas migration through the seal. According to [6], the gas entry pressure in the undisturbed Opalinus clay at 600 m depth below ground amounts to about 5 MPa and thus the gas entry/break-through pressure of the seal in such a situation should be lower than 5 MPa.

The conditions at the MTRL differ significantly from these conditions. According to [7], the overburden pressure at Mont Terri yields a vertical stress of only 7.25 MPa with a horizontal minor stress component of about 2 MPa. Also the porewater pressure amounts to only about 2 MPa so that the gas entry/break-through pressure of the seal in the envisaged SB-experiment is to be kept at a Mont Terri specific level of well below 2 MPa which can be considered a conservative design value if the necessary sealing effectiveness can be demonstrated for this condition.

Swelling characteristics of the buffer

Adequate swelling pressure to obtain the desired sealing effectiveness against formation water inflow. The sealing material will seal itself by swelling when taking up water. The material fills the entire space between the waste canister and the drift wall and any gap remaining from seal construction. High swelling pressure and the capacity for large volumetric strains under free swelling conditions are considered very advantageous [8]. On the other hand, laboratory experiments suggest that gas penetration of an initially water-saturated clay buffer occurs only when the gas pressure slightly exceeds the sum of the swelling pressure and the groundwater pressure [9] [20]. Consequently, in order to cause the gas to flow preferentially through the seal and not into the host rock, the swelling pressure should not exceed the gas entry pressure of the host rock.

3.3.2 General test objectives

The general objective of the SB-project is to test and demonstrate that the sealing properties of clay/sand mixtures given above and studied in preceding laboratory investigations can be achieved and maintained under representative in-situ conditions.

For the successful conduction of the envisaged in-situ experiments, proper installation techniques assuring the required installation densities are very important. In addition, the saturation time of the seal has to be considered in the design of in-situ experiments.

Hence, both the installation technique and the saturation time needed were first to be investigated in large-scale mock-up tests at the GRS geotechnical laboratory in Braunschweig. In the laboratory the seal properties can be tested under ideal and well defined conditions and provide a sound material data basis that can be used to design the in-situ experiment properly and later-on to adequately assess the data gained under not so well defined in-situ conditions at the Mt. Terri URL. This strategy allows for a better assessment of the seal function of the SB materials under real in-situ conditions in a repository.

3.4 Execution of the SB experiment

3.4.1 Mock-up tests

Mock-up 1

The detailed objectives of the mock-up tests are as follows:

- develop and test adequate methods for mixing clay/sand mixtures with adequate homogeneity
- develop and test methods for the installation of clay/sand mixtures with the pre-determined density
- determine the time needed to reach full saturation of the clay/sand seals at different water injection pressures
- determine the permeability to water, the swelling pressure, the gas breakthrough pressure and the permeability after gas break-through; and
- test pre-selected instrumentation and a data collection system for measuring the test parameters.

The first mock-up test was performed from October 2004 until November 2005 by using the most promising 35/65 clay/sand mixture (compare Table 3-4). The achieved installation density of 1.78 g/cm^3 was slightly below the design value of about 1.9 g/cm^3.The test was started by determining the gas permeability, which was determined to 6.5E-14 m^2. Although the installation density in this test was a little bit lower than required, this result corresponds very well with the gas permeability determined in the laboratory tests on small samples.

Afterwards, the seal was saturated with synthetic Opalinus clay solution. At the very beginning, the flow rates had been set too high so that the solution flew along the inner surface of the tube. In order to ensure representative test conditions, the system was closed and kept under atmospheric pressure to allow self-healing of the seal.

After some days, a continuous saturation process with reduced flow rate was initiated. After almost complete saturation of the seal in June 2005, the water permeability was determined to 1.9E-17 m^2, which is in good agreement with the results of the preceding laboratory measurements on small samples. In view of this result, it is assumed that the flow along the inner tube surface was stopped by swelling of the seal element.

For the determination of the remaining swelling pressure, the injection pressure was disconnected at the end of the saturation phase. This is necessary because the injection pressure influences the reading of the sensors for the swelling pressure. Due to the low permeability, the time of the pore pressure drawdown was relatively long. After five days, the pore pressure and the swelling pressure at the injection side ranged about 0.3 MPa. At the upper end, the pore pressure and the swelling pressure amounted to 0.16 MPa and 0.23 MPa, respectively. The higher pressures at the lower position of the sensors might be explained by the water column pressure (hydraulic head) in the seal element. At the very end of the relaxation phase in Nov. 2005, a swelling pressure of about 0.1 MPa was measured at the top, directly underneath the packer,

Inside the seal element the pore pressures ranged between 0.009 MPa and 0.067 MPa and the swelling pressures between 0.012 MPa and 0.028 MPa. Due to the problems at the beginning of saturation, the hydraulic and the swelling properties were possibly influenced by the effect of water flow along the inner surface of the tube. The sealing potential of the 35/65-mixture, however, could be successfully demonstrated in this test.

Mock-up 2

Mock-up 2 was initiated with the improved injection procedure concluded from mock-up 1. The installation density of the seal element, consisting again of a 35/65 clay/sand mixture, amounted here to 1.94 g/cm^3. After installation, the gas permeability was measured first. The determined value of 6.2E-14 m^2 corresponds very well with the gas permeability determined in mock-up 1.

Seal saturation in the initial state was performed at a comparably low injection pressure and only later increased to the foreseen injection pressure of 1.1 MPa.

As can be seen in Figure 3-5, after about 18 months of testing, the total pressure in the seal equalized in the lower and middle part of the seal (red and blue lines) at a value of about 1.1 MPa which corresponds to the applied water injection pressure.

Surprisingly, one does not see a similar evolution of the pressure at top of the seal (green line). However, after a testing period of meanwhile more than 37 months (April 2008), the sealing system seems to approach full saturation with a final total pressure value slightly below 3 bars (Figure 3-5 right). This value would be very close to the swelling pressures determined on the small laboratory samples. Thus, it is very likely that the seal function at full saturation will fulfil the requirements given in Table 3-4.

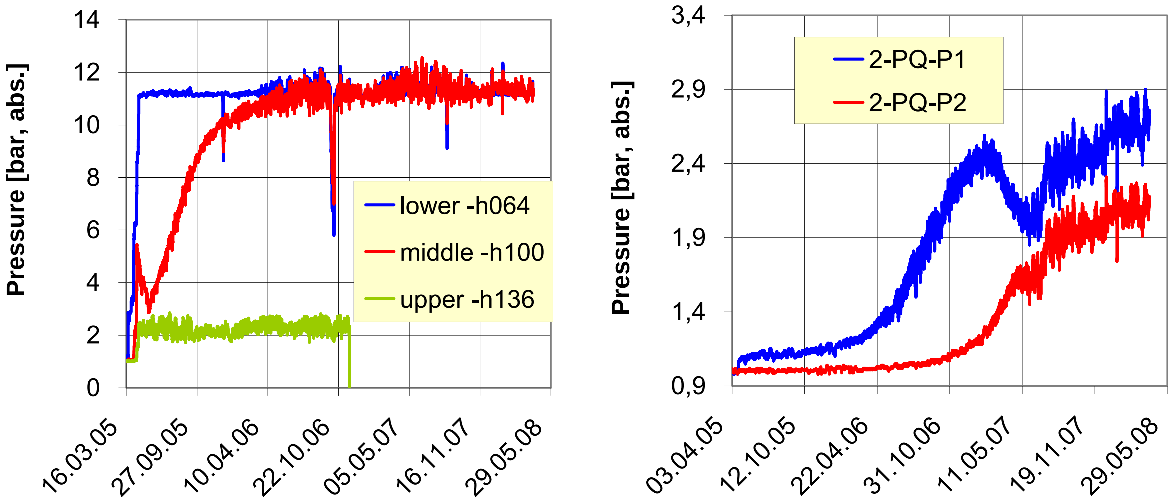


Figure 3-5: Evolution of total pressure in the mock-up
(left: total pressure along the mock-up, right: total pressure at packer bottom)

The first water break-through, indicating a situation close to full seal saturation, was only observed in September 2007, after about 870 days of testing. At this time about 28 litres of water were injected, a value that is about 20% higher than that to be expected for an initial material porosity of about 0.3. Although being very close to full saturation, the seal still takes up very small amounts of water and hence, the pressure monitored at the packer bottom is still slightly increasing.

A first assessment of the seal permeability to water yielded a value of about 1E-18 m^2 which is in very good agreement with the data determined at the small samples used in the laboratory. Also this preliminary result confirms that the required seal function given in Table 3-4 is fulfilled and serves to support the in-situ experiments which are ongoing at the MTRL.

The long time until water break-through exceeds the predicted saturation period (compare paragraph "design calculations" above) significantly. Further research is needed to clarify this discrepancy and to enhance the respective process understanding for further model improvement.

3.4.2 In-situ tests

For the determination of the most interesting material parameters of the moderately compacted clay/sand-mixtures (compare section 3.3.1) the in-situ-experiments are being conducted in the following five stages:

1. **Installation and instrumentation of the individual experiments/boreholes**: Immediately after drilling of the boreholes, the lower porous injection volume, the lower filter frit, the sealing material, the upper filter frit, the packer, and the concrete plug are to be installed by using the techniques tested and eventually improved in the preceding in-workshop tests. On basis of the measured material masses and volumes the clay/sand-ratio and the initial installation density of the moderately compacted clay/sand-mixture are determined.
2. **First gas injection for determination of the initial gas permeability**: At the beginning, dry nitrogen gas is to be injected via the injection tube into the lower injection volume. The injection pressure is to be

adjusted to below 0.1 MPa to avoid a possible flow of fine clay grains out of the seal. The amount of the gas inflow and outflow is to be monitored at the inlet and the outlet of the seal. Comparing the inflow and outflow makes it possible to examine if gas is lost into the surrounding rock. Once steady state flow is achieved, the gas permeability of the seal representing the upper limit is determined.

3. **First water injection to simulate the groundwater flow to the seal and to determine its permeability to water**: After installation, in a repository the seal will take up water from the host rock until full-saturation is reached. The surrounding rock may be first de-saturated due to insufficient water supply from the far region and then re-saturated in a longer period of time. To accelerate the saturation process in the SB experiment, the seal is flooded with synthetic Opalinus clay solution from the lower fluid injection volume. The external water pressure is to be adjusted to below 1 MPa. The amount of injected water and the fluid injection pressure are monitored. Since water content as well as the water saturation are not measured in situ, they are estimated by comparing the in-situ data to well-known laboratory data and modelling results. When the sealing system is saturated and water is collected at the upper filter frit, measurements are continued until steady state water flow is reached. Subsequently, the water permeability of the sealing-system is determined. Shortly before coming to the next step, the water injection pressure is reduced to zero and the remaining swelling pressure of the seal material is determined in comparison to the values measured in the mock-up tests.

4. **Second gas injection to simulate the gas generation in disposal boreholes and to determine the seal gas entry/break-through pressure:** After saturation of the sealing system, dry nitrogen gas is injected again into the lower fluid injection volume to simulate the gas generation in repository rooms. Before this, the water in the lower fluid injection volume is pumped out. The gas injection is started at a low level. The injected and collected gas volumes at the inlet and outlet as well as the displaced water volume are measured. If no outflow of gas can be observed in the upper porous chamber within a certain period of time, the injection pressure is increased stepwise by an increment of 0.1 MPa. After each pressure increment, it is maintained constant for an acceptable time interval. After gas break-through and determination of the gas break-through pressure, the remaining effective gas permeability is determined.

5. **Post-test investigations for determination of the achieved final seal properties:** After termination of the last phase, representative samples are to be drilled from the seal and the surrounding rock for post-test investigations of the achieved in-situ state (density, porosity, water content and saturation…). The data are needed for analyses of the in-situ achieved seal conditions and for calibration of the modelling parameters.

As seen in the mock-up tests, the whole test duration is strongly determined by the saturation phase, which has been predicted in the scoping calculations for the 35/65 clay/sand mixture to about 300 days and for a 50/50 clay/sand-mixture to about 1050 days for the in-situ experiment with a seal length of 1 m and a water injection pressure of 1 MPa. As already explained above, the length of the in-situ experiment using the 50/50 clay/sand-mixture has therefore been reduced to 0.5 m to achieve representative data within the limited project running time.

While the water pressure sensors mounted along the tube wall in the mock-up allow an assessment of the evolution of the seal saturation this is not possible in situ since no instruments are installed in the seal to avoid any bypassing of water along instrument cables. The swelling pressure of the clay/sand mixture, however, which is a useful indicator of the sealing properties, can be also assessed in situ by observation of the total pressure at the two pressure sensors mounted at the bottom of the filter frit at top of the seal (see Figure 3-4).

The first experiment at MTRL using a 35/65 Clay/sand seal has been started in October 2005 and has so far been operated without disturbances. During 30 months of injection, an amount of about 82 l of artificial formation water has been injected into the seal at an injection pressure of about 4 bars under the prevailing in-situ conditions. So far, no water has been collected at the upper outlet which indicates ongoing saturation of the seal, but also a loss of water into the surrounding clay rock as the theoretical amount of water that can be taken up by the porous medium with an initial porosity of about 30% amounts to about 23 litres. The swelling pressure measured at the top of the seal (Figure 3-6) is still increasing slightly and amounts actually to about 1.86 bars. This value is in the same order of magnitude as those determined on small laboratory test samples (compare Table 3-4) and thus, similar sealing properties as those observed on small samples in the laboratory can be expected in this in-situ experiment

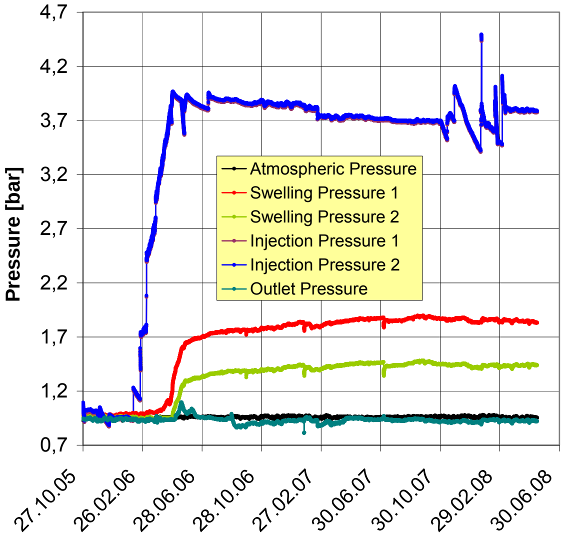


Figure 3-6: Pressure evolution in test borehole BSB2 sealed with a 35clay/65sand mixture

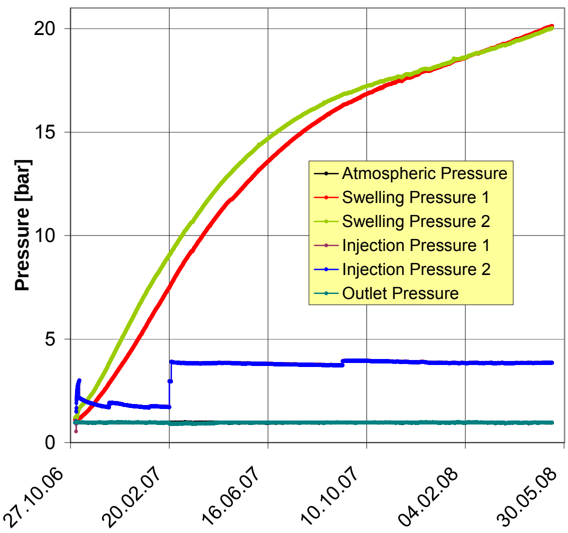


Figure 3-7: Pressure evolution in test borehole BSB13 sealed with pure bentonite granulate (NAGRA material)

On basis of the experiences from the mock-up tests the water break-through at the seal in borehole BSB2 test is expected to occur in late 2008/early 2009.

In accordance with the overall time schedule of the SB-experiment the remaining three in-situ experiments with clay/sand-mixtures of the ratios 35/65, 50/50 and 100/0 have been taken into operation in November 2006.

The test with pure bentonite in borehole BSB13 runs excellently with no disturbances and has meanwhile reached a swelling pressure of almost 19 bars (Figure 3-7). Until end of April 2008, a total amount of 18 litres of water has been injected in this test. The excellent conditions of this test and of that in borehole BSB2 provide a very good basis for the envisaged comparison of the gas permeability behaviour of the different sealing materials, which, according to the test programme, is to be demonstrated at the end of the saturation phase by gas injection tests in all boreholes.

The two experiments with clay/sand-mixtures of the ratios 35/65 in Borehole BSB1 and 50/50 (0.5 m seal length) in borehole BSB15 showed the expected evolution of swelling pressure in the early saturation phase although the initial injection pressure amounted to only 0.5 bar. After increasing the injection pressure in these tests to the same level of about 4 bars as in the pilot test in borehole BSB2, these two experiments located in the southern part of the test niche showed water bypassing to the upper water collection filter frit. This test behaviour is most likely due to a distinct excavation disturbed zone along the borehole wall. Thus, the seal in these two boreholes will be saturated not only through the lower injection volume but very likely to some extent also along the borehole wall. So far 44 and 54 litres of water have been injected into these two test set-ups, respectively.

As mentioned above the first water break-through and seal saturation in the in-situ experiments is expected to occur late 2008/early 2009 in experiment BSB2 with a 35/65 clay/sand seal. Parallel to the remaining determinations of the seal permeability to water and the gas entry/break-through pressure in this experiment during the year 2009, it will have to be decided on basis of actual experimental data how to proceed with the other experiments. It is expected that the general situation in the boreholes showing the bypassing of water will not change in that period of time. For the experiment with the pure bentonite seal in borehole BSB13 it is unknown how long it will take to reach full saturation as no prediction has been made within GRS' scoping calculation programme because of the relatively late decision of NAGRA to support the SB-experiment with this test.

Assuming that the experiment in borehole BSB2 will see the water break-through in early 2009 and the corresponding post-test analyses of this experiment can be finished within 2009, the project duration has been extended to March 2010, so far.

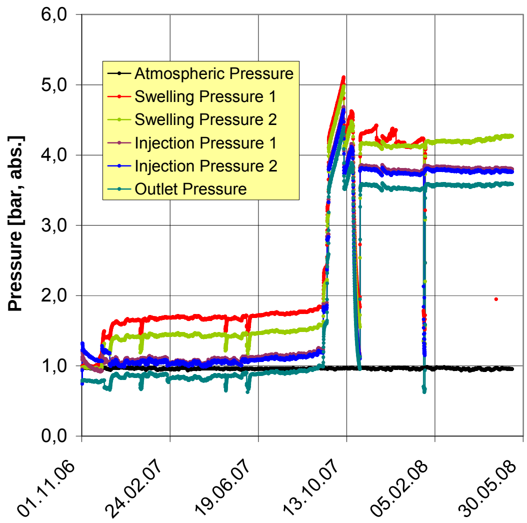


Figure 3-8: Pressure evolution in test borehole BSB1 sealed with a 35clay/65sand mixture

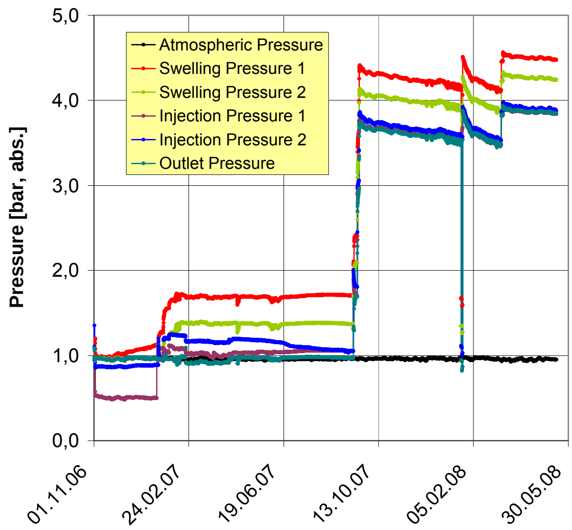


Figure 3-9: Pressure evolution in test borehole BSB15 sealed with 50clay/50sand mixture

3.5 Post-test activities

According to the expected schedule of the in-situ experiments given in the above section 3.4.2 post-test activities will start in the first half of 2009 for the experiment in borehole BSB2. These activities will comprise the drilling of samples from the seal and the surrounding rock for the examination and confirmation of the achieved in-situ state and of those parameters values determined by the evaluation of the in-situ measurements with regard to the permeability to gas and water, and the gas break-through pressure. In addition, as a measure of quality assurance the actual water content, the bulk density, the dry density, and the porosity of the seal material will be determined.

The gained data will be used for an improvement of the numerical simulations of the in-situ measurements and thus for the calibration of the used modelling parameters.

3.6 Analysis of test results and conclusions

3.6.1 Level of success of the test

The preliminary results of the SB-experiments at the MTRL appear to confirm the advantageous sealing properties of moderately compacted clay/sand mixtures which were previously determined on small samples under ideal conditions in the laboratory. The time needed to reach full saturation of the test seals in both the mock-up and the in-situ experiment, however, exceeds the predictions significantly. Further efforts will be needed to clarify the observed discrepancies, to improve the needed process understanding and to develop further the models in use.

3.6.2 Opportunities for the future

As the SB sealing material is meant to be used as a buffer or borehole sealing material in disposal boreholes for HLW in clay formations (compare section 3.1, Figure 3-1) its thermal behaviour and thus its thermal properties are still to be determined in addition to the tests performed so far under isothermal conditions.

GRS together with other Mt. Terri partners and also German partners is therefore currently working on the development of project proposals which comprise besides the necessary laboratory determination of the thermal properties in-situ investigations of the thermal behaviour, especially in the early stage of a HLW repository.

Generally, clay materials show a lower thermal conductivity in comparison to crystalline or salt rocks. Thus, heat dissipation is slow in clay formations and hence, high temperature gradients will prevail in the repository near field, especially as long as the buffer exhibits a low conductivity because of being not re-saturated due to water uptake from the host rock and/or compacted due to creep of the host rock.

Thanks to its sand content, the SB material shows in addition to its advantageous hydraulic properties a higher thermal conductivity. Favourable near-field conditions will therefore take place in a HLW repository in clay formation when using this buffer material instead of highly compacted pure bentonite buffers considered in many other concepts. **The continuation of R&D on the suitability of the SB material as an alternative will thus remain in the focus of GRS' future R&D geotechnical research on the clay option**.

4 IN-SITU SEAL INSTALLATION TEST (BY EURIDICE)

4.1 Test installation

4.1.1 Concept and general design

The PRACLAY seal consists of a steel structure closing the PRACLAY gallery. Around the steel structure bentonite will be placed against the clay massif. The bentonite will be hydrated to close the EDZ around the seal. The seal will be placed in the PRACLAY gallery, which has a nominal inside diameter of 1.90 m, an external diameter of 2.50 m and a length of 45 m. The lining consists of concrete wedge blocks. In the zone where the hydraulic seal will come, an alternative lining is placed (Figure 4-1). This alternative lining consists of a temporary and permanent part. The permanent part is made up by 4 rings, 80 mm wide and 110 mm thick. The rings are not solid parts, but are made of circumferential sections. Steel plates are placed between these rings. Behind the rings wood is placed to support the clay massif. The wood will be removed before the installation of the hydraulic seal. A part of the steel plates stays in place to support the rings after the removal of the wood.

The "upstream" side of the seal is the side of the heated part of the PRACLAY gallery. The "downstream" side is the side towards the Connecting Gallery. In its final state, the structure will be subjected to a radial pressure of 5 MPa caused by the bentonite when a uniform pressure distribution is considered. In the case of an elliptic pressure distribution, the radial pressure varies between 4 and 6 MPa. On the upstream side, there will be a pore water pressure of 3.5 MPa and a temperature of 90°C for the duration of the heater test, which is 10 years. On the downstream side there will be atmospheric pressure and a temperature of 16°C. These conditions and the location of the steel structure are illustrated in Figure 4-2.

The seal also has to allow feed-through of the instrumentation placed inside the gallery. This will be achieved by openings in the seal. After the installation of the instrumentation, the openings will be sealed.

Figure 4-1 : Lining in the zone where the hydraulic seal will be placed

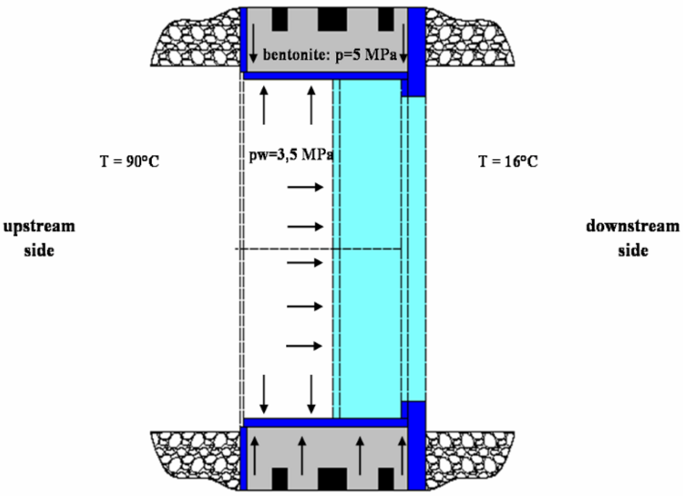


Figure 4-2 : Steel structure: nominal operating conditions and location

The general concept of the seal is given in Figure 4-3 and Figure 4-4.

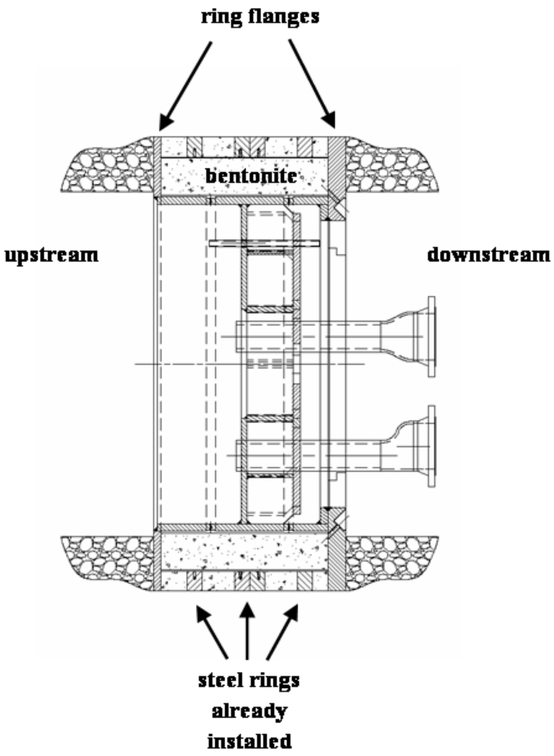
The general seal concept consists of two flanges placed against the concrete lining and a cylinder with an external diameter of 1.84 m. The cylinder is further equipped with stiffeners, pipes to provide penetrations for instrumentation and openings for hydration of the bentonite and a closing plate to finally seal off the heated part of the PRACLAY gallery.

Figure 4-4 provides a view from the downstream side of the seal revealing the opening in the seal. Before the closing plate is assembled, the opening provides a manhole for the installation of instrumentation and material (heating system, backfill) in the upstream part of the part of the PRACLAY gallery. H1 is the pipe in the closing plate. The other openings allow instrumentation feed-through.

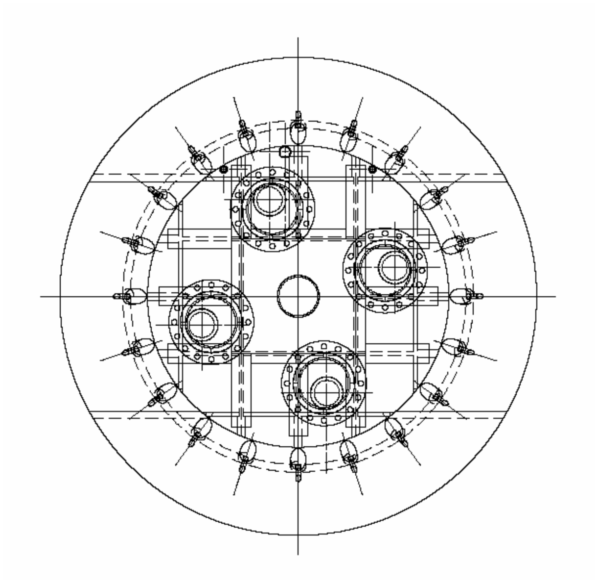
The length of the seal was set at 1 m. The influence of the seal length on its efficiency as a hydraulic cut-off (i.e. on the thermally induced pore water pressure build-up) has been studied numerically. Figure 4-5 shows the impact of the seal length on the pore pressures profile at the mid plan of the heater. Without a seal the pore pressure build-up is similar to that under drained condition. A seal of 1 m and one of 15 m are nearly equivalent beyond 10 m into host rock, even after 10 years of heating. A length of 1 m was finally chosen for the PRACLAY seal.

After the removal of the temporary part of the lining, the upstream ring flange and subsequently the downstream ring flange are installed (Figure 4-6a and Figure 4-6b). Then the bentonite blocks (Figure 4-6c) are installed and finally the cylinder is brought in place and welded to the downstream flange (Figure 4-6d).

The different parts making up the seal are discussed in following section. No negative tolerances on the thicknesses of the pressure retaining parts (cylinder, flanges and closing plate) are allowed and when eventual machining (cutting, welding, etc.) is performed on these parts, it has to be guaranteed that the designed thickness is maintained. All welds and repairs are inspected on their whole surface for defects as crack, tear, fish eyes, and lack of penetration, lack of fusion or crack initiating inclusion.



(a)



(b)

Figure 4-3 : General design of the seal: (a) axial cross-section, (b) view from the downstream side

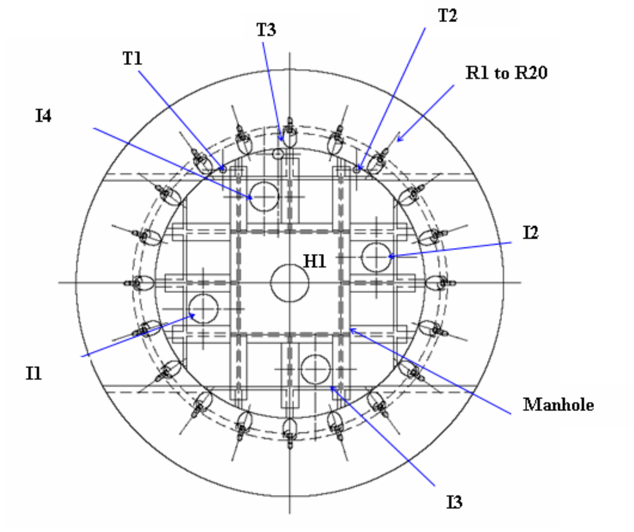
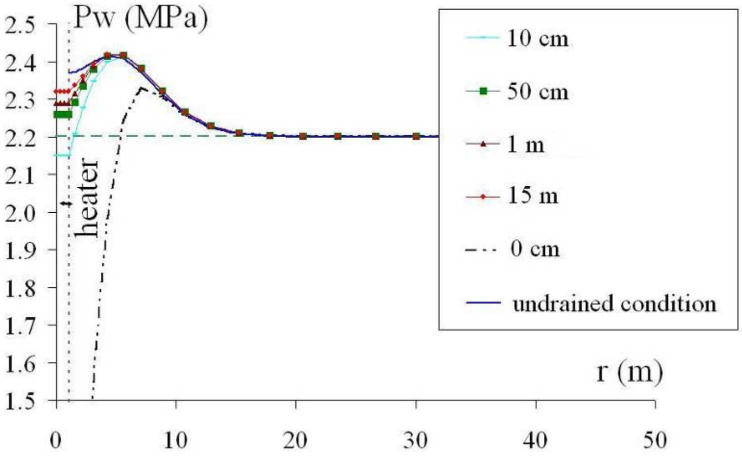
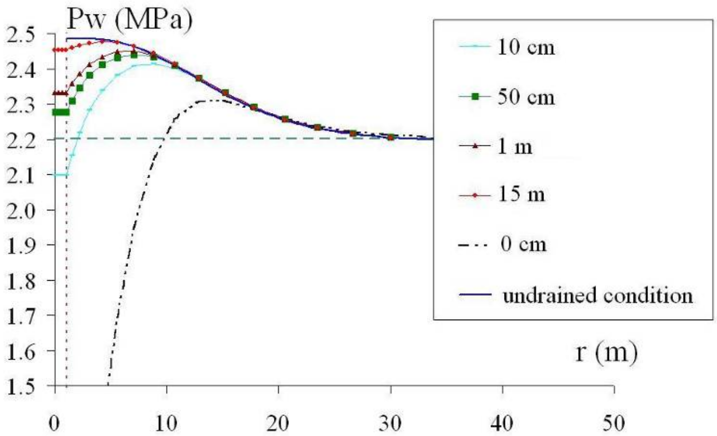


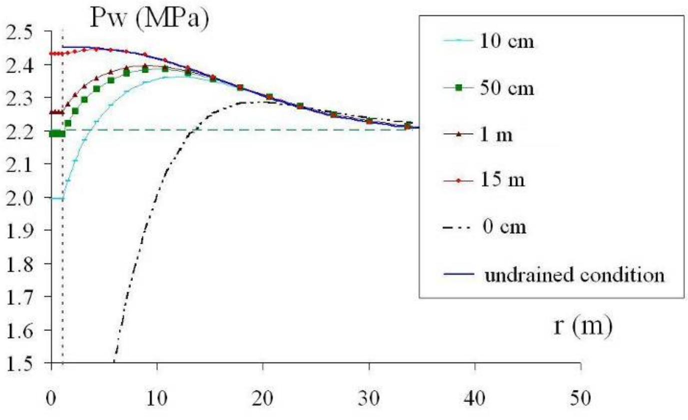
Figure 4-4 : Downstream view of the hydraulic seal revealing the openings in the seal



1 year



5 years



10 years

Figure 4-5 : Radial pore pressure profiles at mid-plane of the heater considering different seal lengths

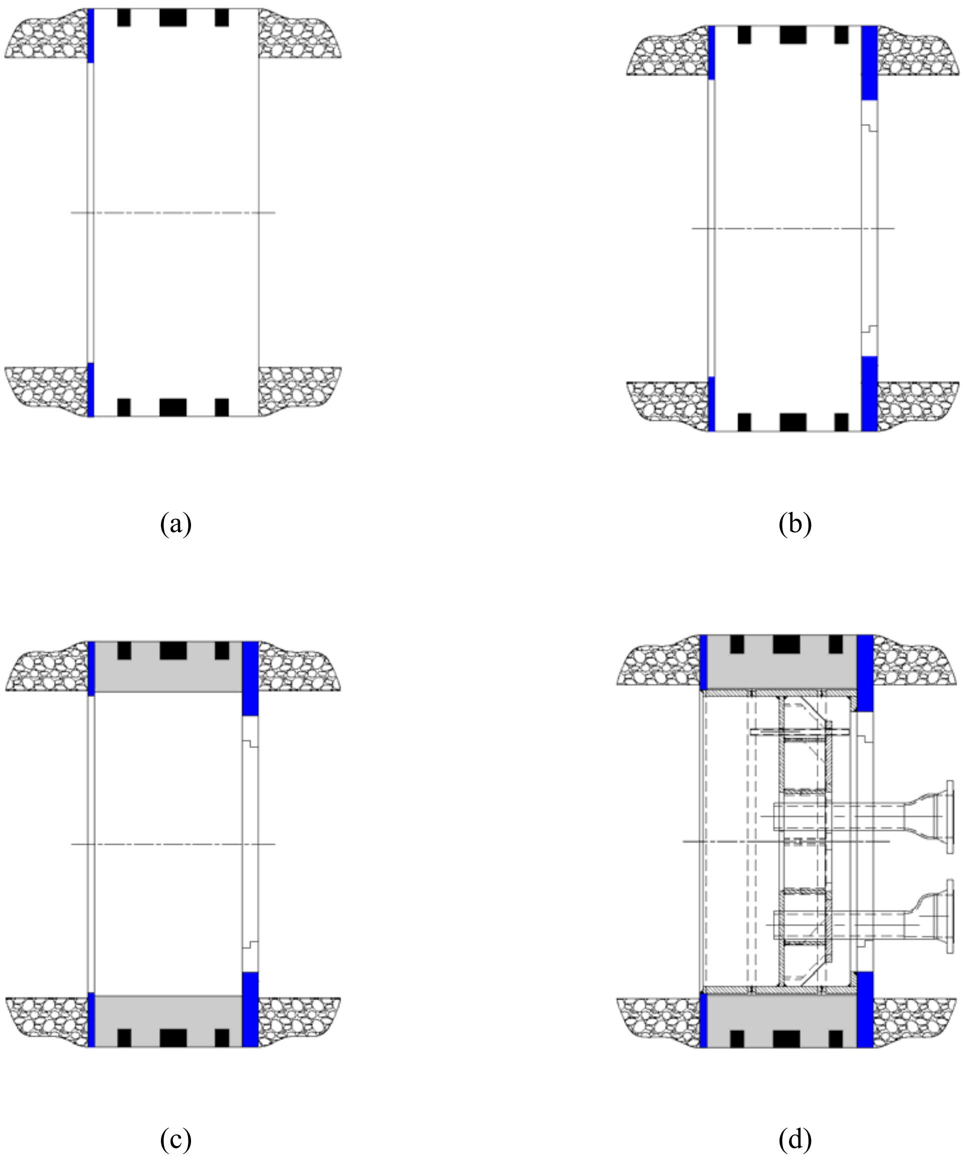


Figure 4-6 : Installation sequence: (a) installation of the upstream flange; (b) installation of the downstream flange; (c) installation of the bentonite; (d) installation of the cylinder pore pressure profiles at mid-plane of the heater considering different seal lengths

4.1.2 Seal components

Flanges

The downstream flange is 100 mm thick, the upstream flange 40 mm. They have an external diameter of 2500 mm. The internal diameters of the downstream and upstream flange are respectively 1580 and 1840 mm. They both are installed in 4 parts and are welded together on site. The 100 mm flange is placed against the concrete lining. Any irregularities on the contact surfaces will be filled (e.g. by silicone rubber sheets).

The material for the 40 mm thick flange is SA240-304. The material for the 100 mm thick flange is SA182-F51.

The cylinder will be drawn to the bearing of the downstream flange and will be welded to it. This flange is foreseen with 20 openings (see R1 to R20 in Figure 4-4) that are placed circumferentially to allow feed-through of instrumentation to the bentonite blocks.

Bentonite blocks

The bentonite has to provide:

- A permeability as low as possible, one or two order lower than that of the Boom Clay itself. i.e. a lower than 10^{-14} m/s at its saturated state is desirable.
- A suitable swelling pressure, lower than the in-situ lithostatic pressure at long term is required. The designed value for the PRACLAY seal is 4.5 – 5 MPa.

The bentonite blocks that will be used, are MX-80 WH2 and are fabricated by MPC (France). The choice for this type of bentonite is mainly based on literature related to the permeability, swelling capacity, water retention capacity, existing THM laboratory testing data, compatibility with the Boom Clay's environment, etc. The design and characteristics of the blocks were determined by numerical scoping calculations. These are described in section 4.2.

The configuration of the bentonite blocks in the seal is illustrated in Figure 4-7. The blocks will be installed in two layers.

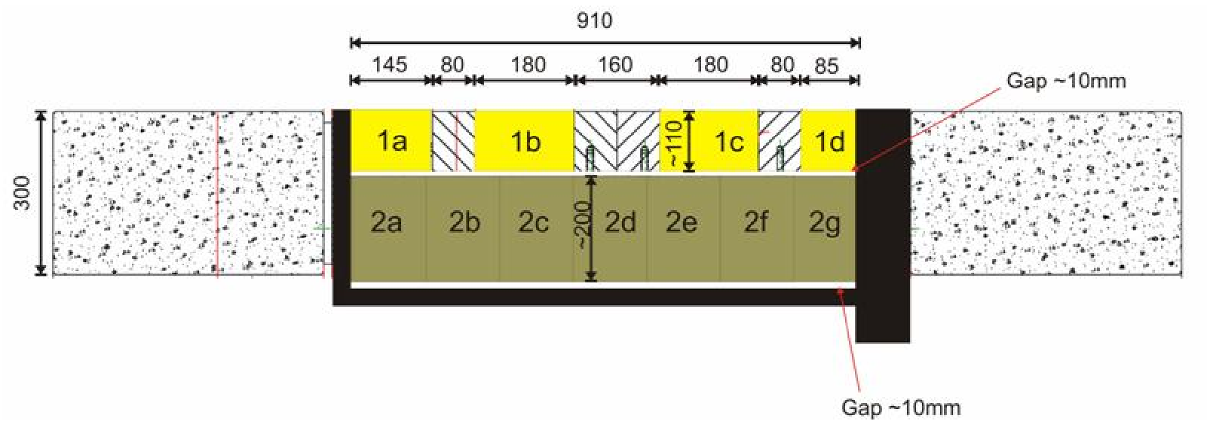


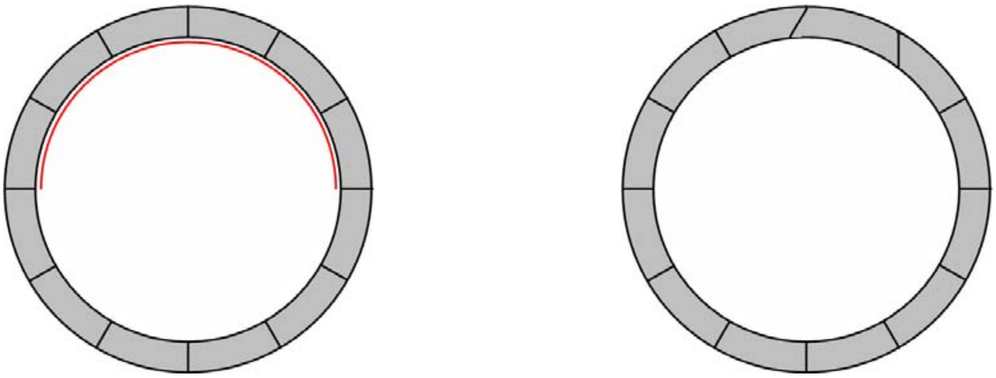
Figure 4-7 : Configuration of the bentonite blocks (to be placed in two layers)

Note that these dimensions are only indicative. Their final dimensions will be determined by the technological voids. Two void layers are foreseen as can be seen in Figure 4-8. The dimensions of the bentonite blocks will be adjusted to achieve the designed gap sizes. The ratio of the initial void volume over the initial bentonite volume is estimated to be about 8 to 10%. In the fabrication of the bentonite blocks, two moulds will be used; one for each layer. The fabricated blocks will be cut into their desired dimensions on site. The fabricated blocks of layer number 1 will weigh approximately 15.5 kg, the blocks of layer number 2 approximately 13 kg.

Figure 4-8 : Technological void (10 mm) between the bentonite layers and between the inner bentonite layer and the cylinder

The installation of the blocks will be according to the sequence given in Figure 4-9. The blocks of the first ring will be kept in place by welding small pieces to the steel rings. The blocks of the second layer will be installed from bottom to top. The blocks in the upper part top can be placed by using a support structure (drawn in red) where the blocks are slid in from the side (Figure 4-9a). For the blocks of the last ring it is not possible to install the blocks from the side (Figure 4-9b). Therefore the support structure will not be used for this ring; the blocks have to be attached to the existing structure. The last block will be cut into a different shape to make it possible to insert the block from below.

During the on site welding, the maximum temperature of welded parts in contact with the bentonite will always be less than 200°C.



(a) (b)

Figure 4-9 : Installation sequence of the bentonite blocks

Cylinder

The external diameter of the cylinder is 1840 mm. No positive tolerance on the external diameter is allowed to assure the transport of the cylinder through the PRACLAY gallery. Stiffeners are assembled to the cylinder. The material for the cylinder and stiffeners is SA240-304. Grade 304L is also accepted if the mechanical properties meet the requirements of the grade 304.

The cylinder is completely assembled before transporting it to the underground gallery except for the closing plate. The closing plate is left out to provide the cylinder with a manhole. The manhole allows placing instrumentation and material (heating system, backfill) in the upstream part of the gallery. After this, the cylinder is closed by welding the closing plate to the cylinder. The closing plate is foreseen with a central pipe to give access to the back-up heating system.

Different openings are foreseen to allow feed-through of the instrumentation and heating system placed in the upstream part of the gallery (Figure 4-4). These penetrations are realized by pipes, flanges and counter-flanges, bolting and gaskets.

Injection filters for the bentonite hydration are placed on the exterior of the cylinder. The configuration of the injection system is given in Figure 4-10. The filters are placed on the exterior of the cylinder. Two rings of filters are installed: in cross-section A-A and in cross-section B-B (Figure 4-10). The filters are 50 mm wide and 3 mm thick. They are placed in an opening leaving 1 mm void above and below the filter. The filters do not cover the complete circumference. They cover 4 radial sections of 65°. There is a difference of 45° between the filter sections in cross-section A-A and cross-section B-B. Each filter is fed by two channels, each on one side of the filter. These channels are 6 mm in diameter. The material of the filters is steel grade 304(L) and the filter openings are about 0.5 to 1 µm. For the injection synthetic Boom Clay water will be used. The injection parameters (pressure, flux, etc.) need to be decided in the future.

Closing plate

A manhole is left open in the centre of the cylinder to allow installation of the heating system and backfill material in the upstream side of the PRACLAY gallery (Figure 4-4). After this installation and after the hydration of the bentonite, the manhole is closed by welding a 600 x 600 mm plate to the cylinder. The plate has a thickness of 40 mm. The plate contains a central pipe with an opening of 221 mm in diameter to give access to the heating system (H1 on Figure 4-4). The material for the closing place is the same as for the cylinder.

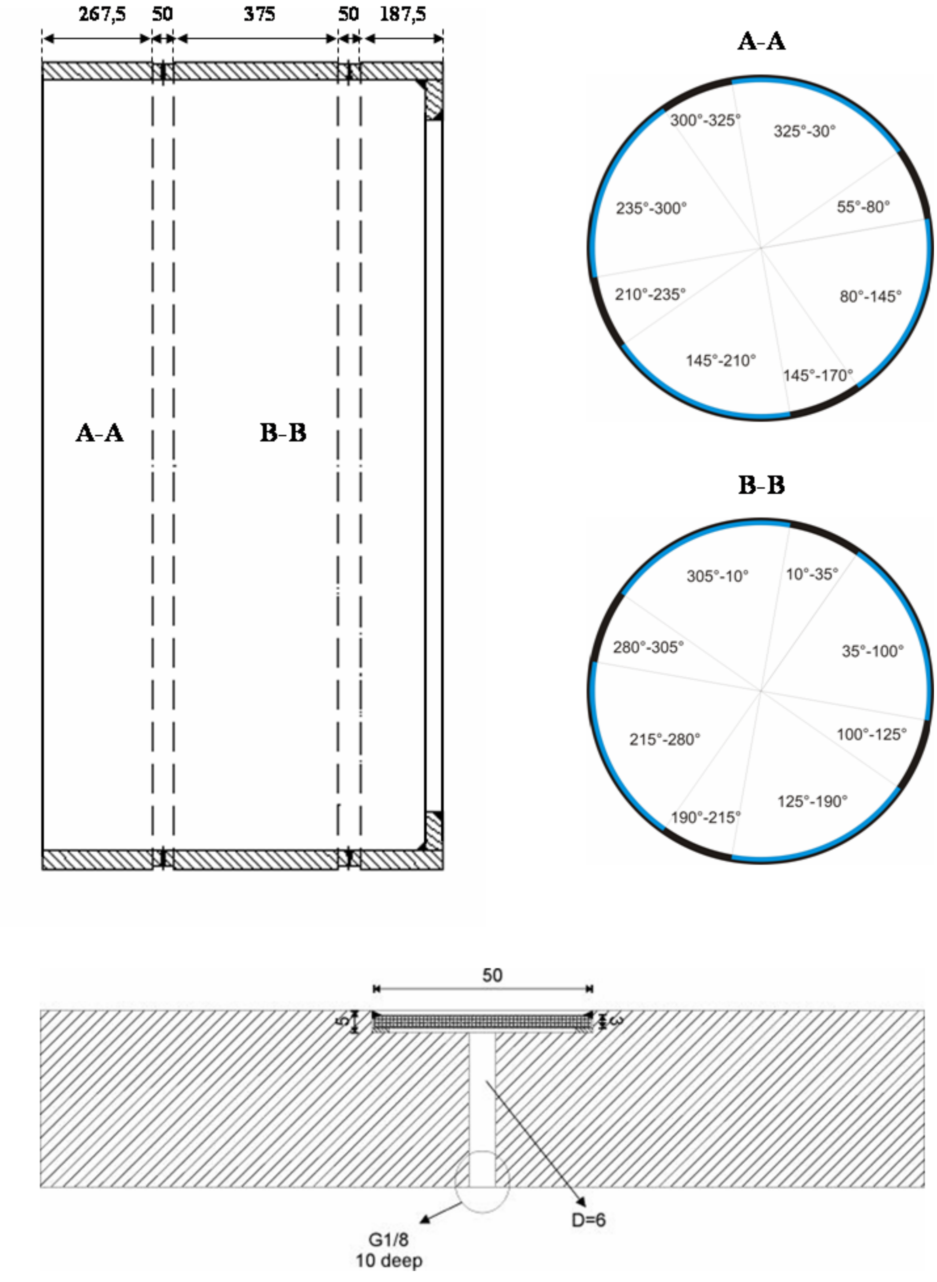


Figure 4-10 : Configuration of the injection system

4.2 Swelling material

4.2.1 Selection of MX-80 as swelling material for the PRACLAY seal

Several physico-chemical properties of different types of bentonite are given in Table 4-1 and Figure 4-11. The Na (-rich) bentonite MX-80 presents apparently higher plasticity and water retention potential than a Ca (-rich) bentonite like FoCa.

Table 4-1 : Main physico-chemical properties of different bentonites (From Tang, 2002) [10]

Properties	FEBEX	Kunigel	MX80	FoCa
Montmorillonite content (%)	82	48	80	40
Particle density (Mg/m^3)	2.70	2.79	2.76	2.67
Liquid limit (%)	102	474	519	112
Plastic limit (%)	53	27	35	50
Plasticity index	49	447	484	62
Clay (<2μm) content (%)	68	64.5	60	80
CEC (meq/100g)	115	73.2	82 .3	69.1
Na^+ (meq/100g)	27	40.5	79.8	2.64
Ca^{2+} (meq/100g)	44	28.7	5.28	62.9

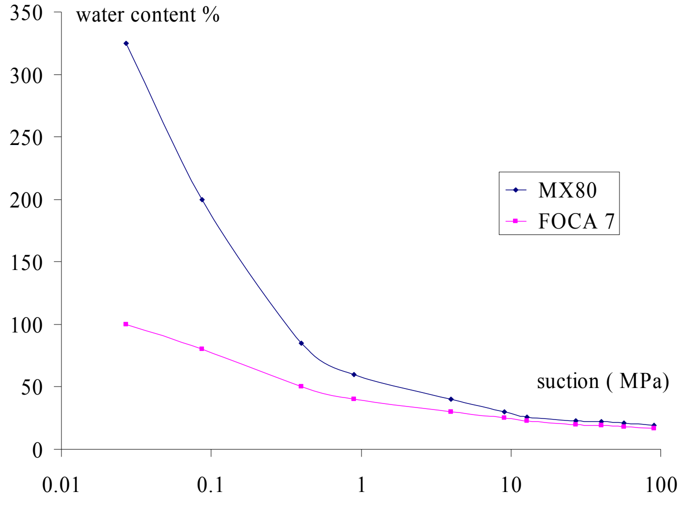


Figure 4-11 : Water retention of MX-80 and FOCA clay (from Marcial, 2002)

Figure 4-12 shows the gathered results of laboratory swelling pressure tests on different bentonites. It seems that, due to the difference in microstructure, Na bentonite presents higher swelling potential than the Ca bentonite. However, this difference diminishes when the dry density increases.

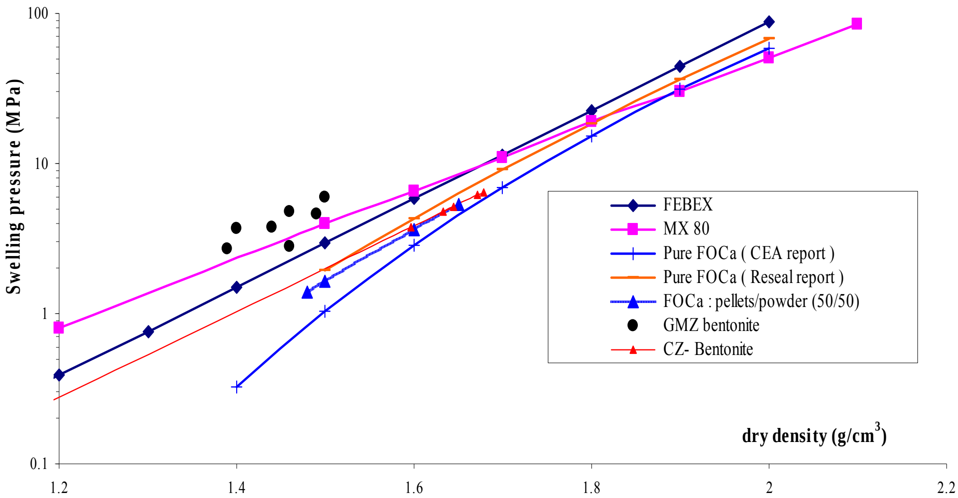


Figure 4-12 : Swelling pressure of different bentonites as a function of the dry density

Further, it should be mentioned that Na bentonite is compatible with the Boom Clay environment, whose water chemistry is sodium-dominated (14 mM $NaHCO_3$).

There are actually no strict criteria for the choice of bentonite for the seal. It was decided however to use MX-80 based on the above mentioned more favourable characteristics. Moreover, the experience from other URLs will allow a knowledge exchange on MX-80.

Laboratory test results are important to deduce the THM parameters for numerical scoping calculations, which can provide a guideline for the design of the test, especially for the initial dry density of the bentonite. The initial dry density is a dominant factor to control the swelling pressure and necessary saturation time. For MX-80, a series of laboratory tests have been performed at CIEMAT, CEA, CERMES and SKB that allowed getting sets of these parameters.

The MX-80 will be compacted to a desired initial dry density on the basis of numerical scoping calculations taking into account the interaction with Boom Clay as well as the technological voids resulting from installation.

4.2.2 Numerical scoping calculations (computer simulations), to determine initial dry density of bentonite blocks

General

The initial dry density of the bentonite blocks is a most important parameter controlling the swelling pressure as well as the final saturated permeability. The technological voids that will be present after the installation are an important parameter and play a role in choosing the initial dry density.

A series of scoping calculations were performed to study the THM interaction between the bentonite seal and the Boom Clay. The initial dry density of the bentonite blocks for the PRACLAY seal will be determined on the basis of these numerical simulations.

Following important aspects were studied:

- effects of the technological voids on the behaviour of the seal, especially in terms of swelling pressure generation.
- effects of artificial injection on the hydration process. Different injection pressures and durations were studied.

Meanwhile, a set of parametric sensibility analyses were performed, especially on the influence of the saturated permeability on the seal behaviour.

The numerical simulations were performed using CODE_BRIGHT 3.0 which is a finite element code developed by Technical University of Catalonia (UPC) and the Centre for Numerical Methods in Engineering (CIMNE). The unsaturated bentonite is treated as a multi-phase and multi-species system. The soil is a three-phase system of solid (s), liquid (l) and gas (g). The liquid phase includes two species of liquid water (w) and dissolved air (a) and the gas phase includes two species of dry air (a) and water vapour (v).

According to MPC, the company in charge of fabrication of the bentonite blocks for PRACLAY seal, the maximum attainable water content during compaction is about 18 %, a minimum dry density is about 1600 kg/m^3. Numerical studies focused thus on the initial dry density higher than 1600 kg/m^3.

1D simulations

In a first stage, 1D (1-dimensional) THM modelling was performed in order to get an insight in the THM interaction between bentonite and Boom Clay and to delineate the most important influential factors to THM responses. Numerous cases considering different gaps, different initial permeabilities, different injection pressures/durations, different initial dry densities were studied. The gap simulates the technological void which is assumed to be concentrated to the innermost part of the seal close to the confining steel cylinder. Four gaps are considered: 0, 1.5 cm, 3 cm, and 4.25 cm corresponding to the technological voids (ratio of the initial void volume over the initial bentonite volume) of 0%, 4.1%, 8.7% and 13 % respectively. The initial saturation degree of bentonite is about 74.6% for dry density of 1700 kg/m^3 and 75.8% for dry density of 1800 kg/m^3, determined from the water retention curves assuming a water content of 18%.

Figure 4-13 shows the steady swelling pressure at bentonite/Boom Clay interface as a function of the technological voids. Figure 4-14 summarises the swelling pressure obtained in different cases. The results indicate that, for a given initial dry density, the steady swelling pressure is mainly controlled by the technological voids. The saturated permeability as well as the artificial injection has little influence on it. Bentonite of 1700 kg/m^3 generates about 1-1.2 MPa more swelling pressure than that of 1800 kg/m^3.

The saturation process is illustrated in Figure 4-15 where, a minimum saturation degree inside the bentonite at one moment was defined, because of the localised presence of the injection filters, the saturation degree inside the bentonite before full saturation is not homogeneous. Three saturation states with minimum saturation degree reaching 95%, 99% and 100% in the bentonite are given for all cases studied. It can be seen that the time distance between lines of saturation states 100% and 99% is much bigger than that between 95% and 99%, so it takes very long time for the bentonite to get the last 1-2 % of saturation. Besides, it can be seen that the permeability plays a much more significant role than void ratio on the time needed to reach a saturation degree of 95% and 99%. To reach full saturation, technological void ratio also plays important role. The time to start heating is also included in Figure 4-15, from which it is found that for most cases, 95% saturation state has been reached when heating starts. If injection is carried during 6 more months, more than 99% of saturation degree can be reached before heating (case 14).

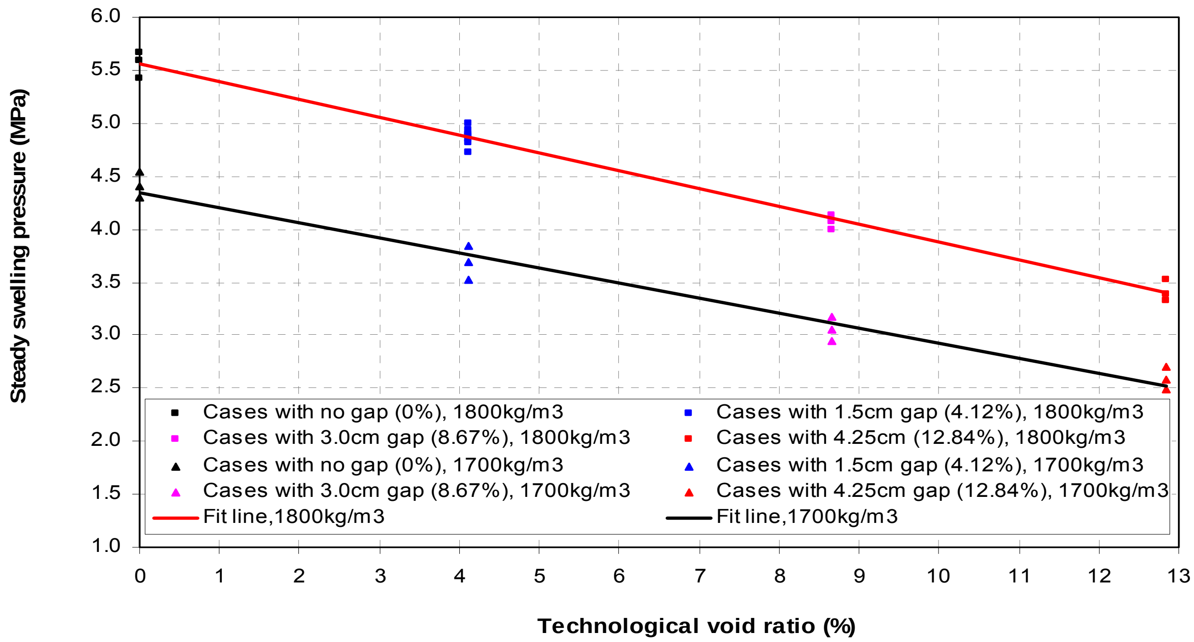


Figure 4-13 : Variation of swelling pressure at gallery inner surface with technological void ratio for different initial dry density : 1700 kg/m^3 and 1800 kg/m^3

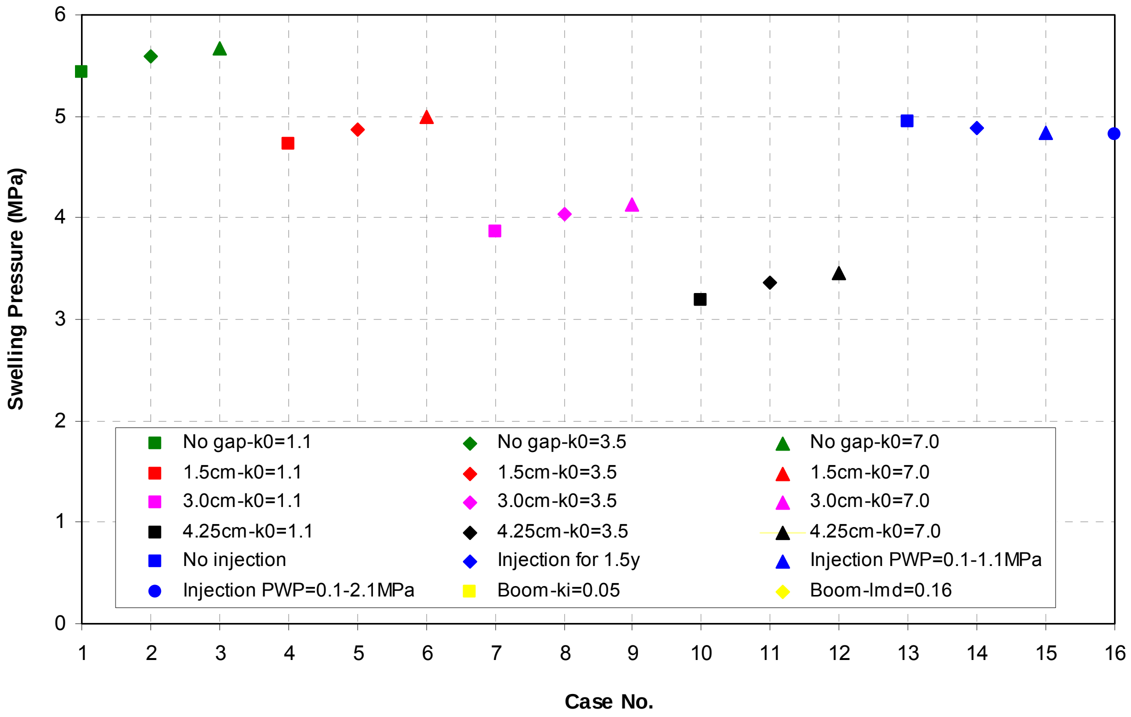


Figure 4-14 : **Swelling pressure of bentonite with dry density 1800kg/m^3 in different cases**

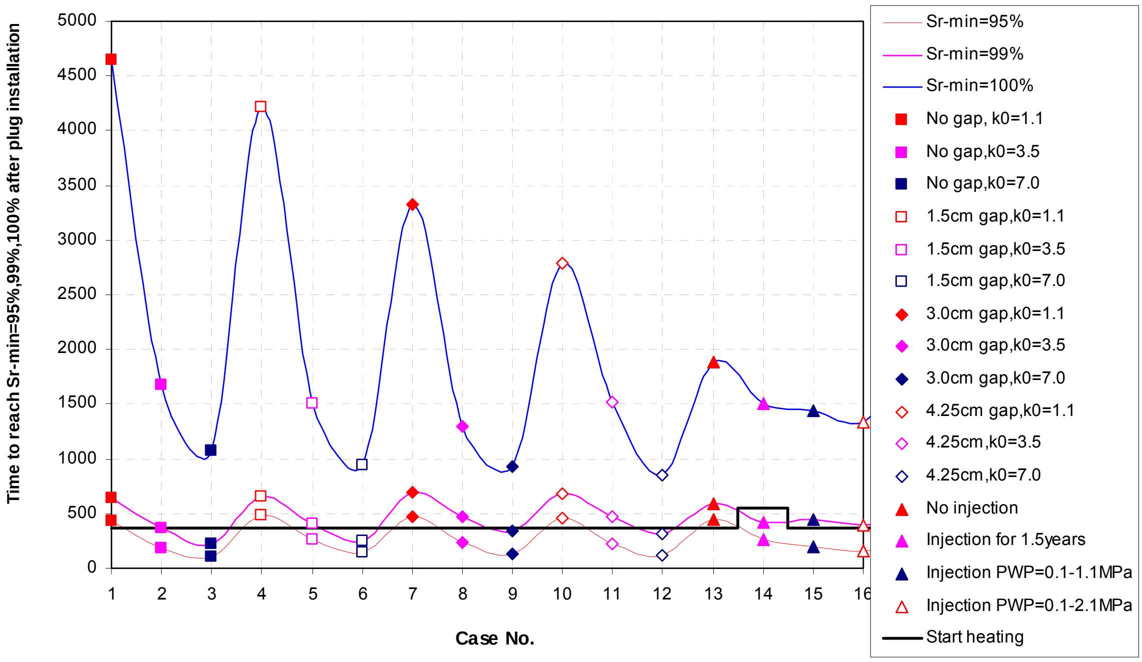


Figure 4-15 : **Time to reach minimum saturation degree of 95%, 99% and 100% with dry density 1800 kg/m3 in different cases**

2D simulations

In a second stage, 2D (2-dimensional) axi-symmetrical modelling taking into account all parts of the PRACLAY experiment were carried out.

The permanent steel rings in the seal zone were included in the model. An axi-symmetric geometry around the axis of the PRACLAY Gallery is used. Consequently, the Connecting Gallery (CG), which is the gallery perpendicular to the PRACLAY gallery and 10 m from the place where the seal will be installed, cannot correctly be included in this axi-symmetric configuration. However, the initial pore pressure distribution around the PRACLAY seal prior to the excavation of the PRACLAY gallery is strongly influenced by the CG, only 3D geometry can consider the real geometry of the CG, but it is computationally expensive. In order to study its effect on the seal behaviour, two geometries with different boundary conditions are adopted, one ignores the CG, and the other one uses a hypothetical hydraulic boundary condition to produce the initial pore pressure around the PRACLAY gallery. Similarly to 1D modelling, different cases considering different gaps, different injection strategies, and different saturated permeabilities are studied.

The gap simulates the global technological void inside the confining structure which is assumed to be concentrated to the innermost part of the seal close to the confining steel cylinder. Because of the permanent steel rings, the equivalent technological void ratio corresponding to the same gap is different from that in a 1D model, accordingly, gaps of 1.5 cm, 3.0 cm and 4.25 cm correspond to 4.8%, 10% and 15% technological void ratio respectively.

Figure 4-16 shows the steady radial stress distribution along the interface between Boom Clay, steel rings and bentonite under several typical cases. Obviously, compared to the 1D model, the presence of steel rings leads to a highly inhomogeneous distribution of the swelling pressure.

Figure 4-17 gives the evolution of the maximum steady radial stress (swelling pressure) at the interface Boom Clay/bentonite/steel rings in function of equivalent technological void ratio. Clearly, it's the technological voids which control the swelling pressure.

Due to the presence of the steel rings and localised injection filters, the swelling pressure distribution inside the bentonite is not homogeneous. Figure 4-18 gives the radial stress distribution along the interface bentonite/confining cylinder (inner face of the bentonite). Compared to the radial stress along the interface Boom Clay/bentonite/steel rings (Figure 4-16 and Figure 4-17), the stress is nearly doubled along the inner face for a dry density of 1800 kg/m^3. At the corner of the flange of the confining structure, the stress is further increased due to the boundary condition.

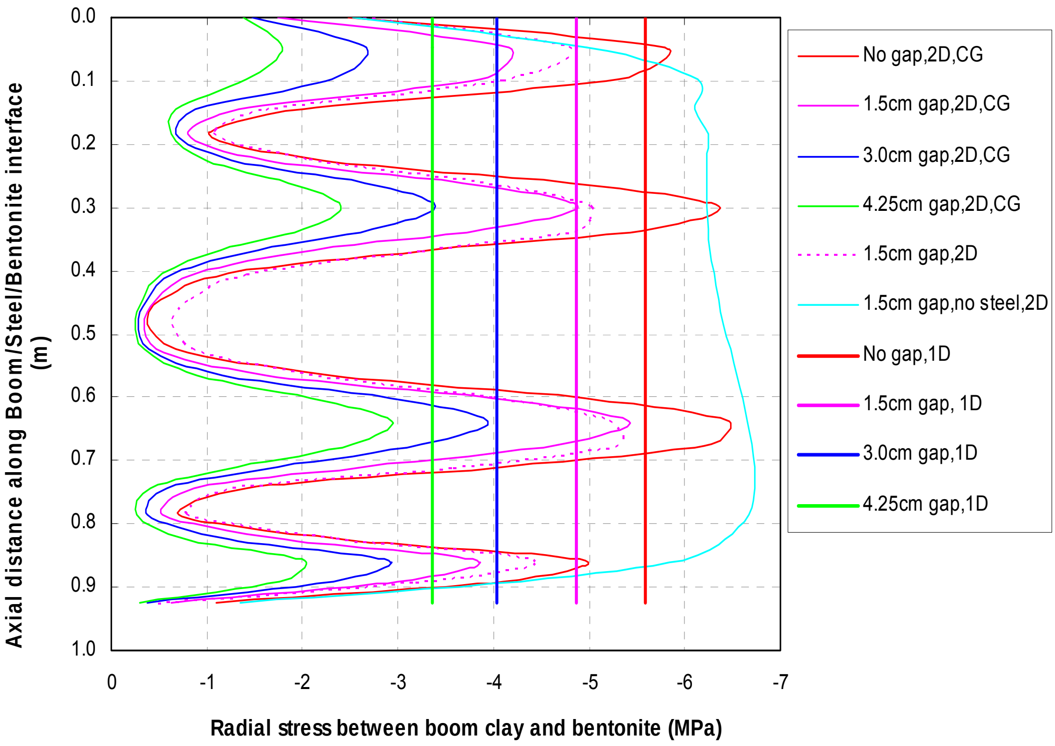


Figure 4-16 : Steady radial stress distribution along the interface between Boom Clay and steel, bentonite in several typical cases

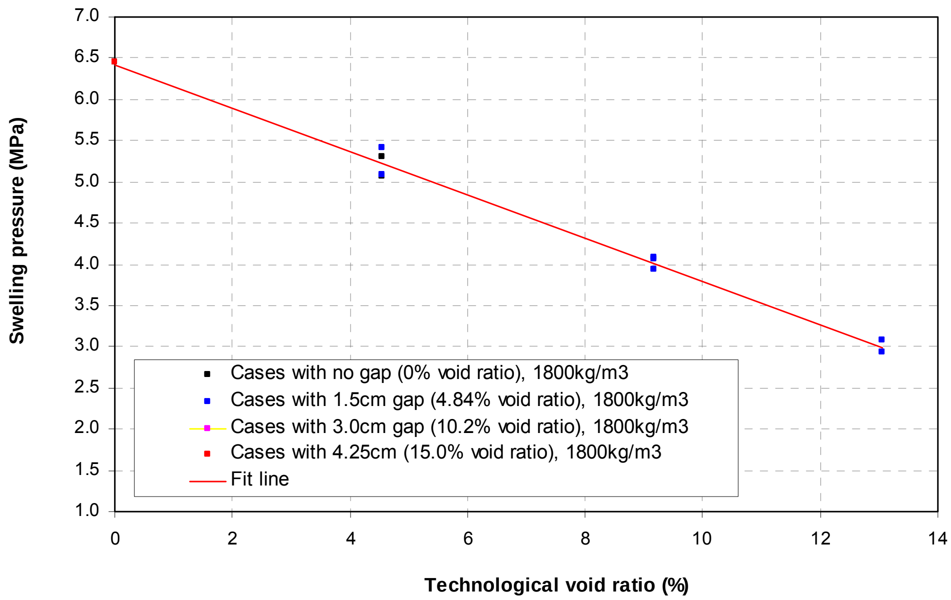


Figure 4-17 : Variation of maximum steady radial stress between steel, bentonite and Boom Clay with technological void ratio

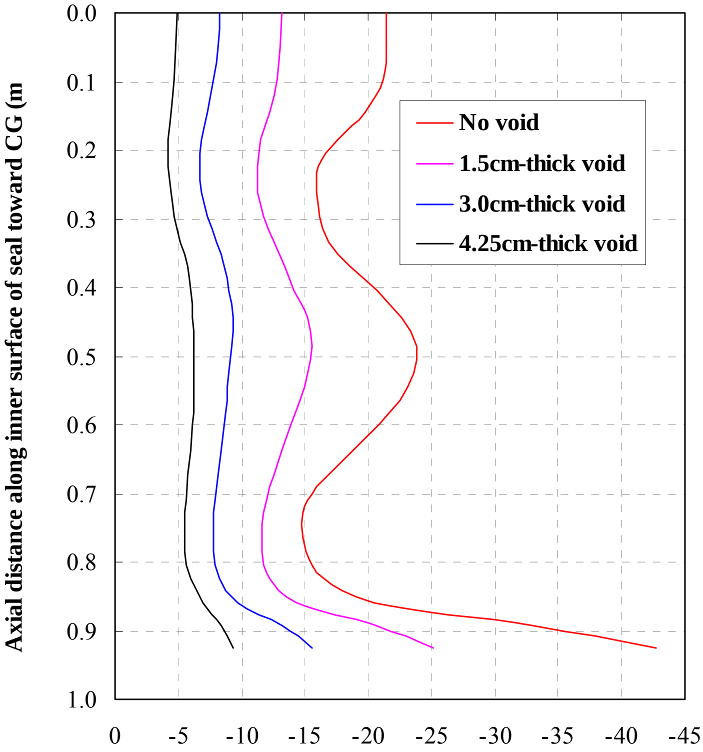
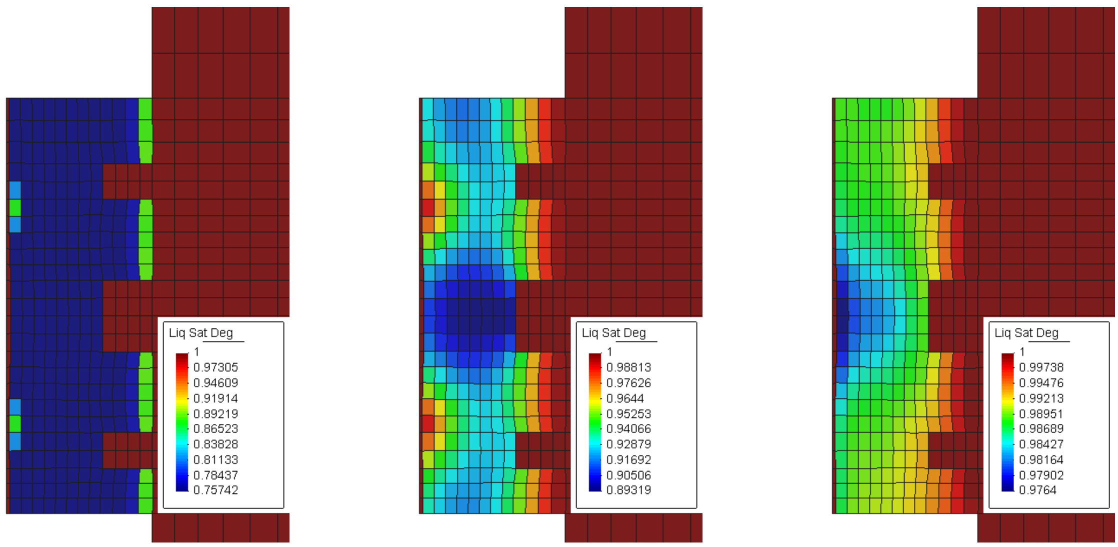


Figure 4-18 : The radial stress distribution along the interface bentonite/confining cylinder (inner face of the bentonite; after 10 years of heating)

Due to the presence of the steel rings and localised injection filters, the saturation degree inside the bentonite before full saturation is reached is inhomogeneous as shown in Figure 4-20. A minimum saturation degree at one moment is then defined. Figure 4-20 illustrates the time needed before reaching saturation states with a minimum saturation degree of 95%, 99% and 100%. Like in the 1D simulation, the time distance between lines of saturation state 100% and 99% is much bigger than that between 95% and 99%, so it takes a very long time for the bentonite to reach the last few % of saturation. Besides, it is also indicated that the permeability plays a much more significant role than other factors such as technological voids, injection condition and geometric model on the saturation state reaching saturation degree of 95% and 98%. The time to start heating is also included in Figure 4-20, from which it is found that for most cases, 95% saturation state has not been reached when heating is scheduled to start. An additional injection during 6 months seems to bring the bentonite to a higher saturation level than 95 %.

Hence, waiting till full saturation to start heating phase seems unrealistic, since the last 1-2 % of saturation requires extremely long time.



(a) 1 day (b) 1 year (c) 1.5 year

Figure 4-19 : Contour of saturation degree at three different times after injection (for case with 1.5 cm gap, dry density of 1800kg/m3, without CG consideration)

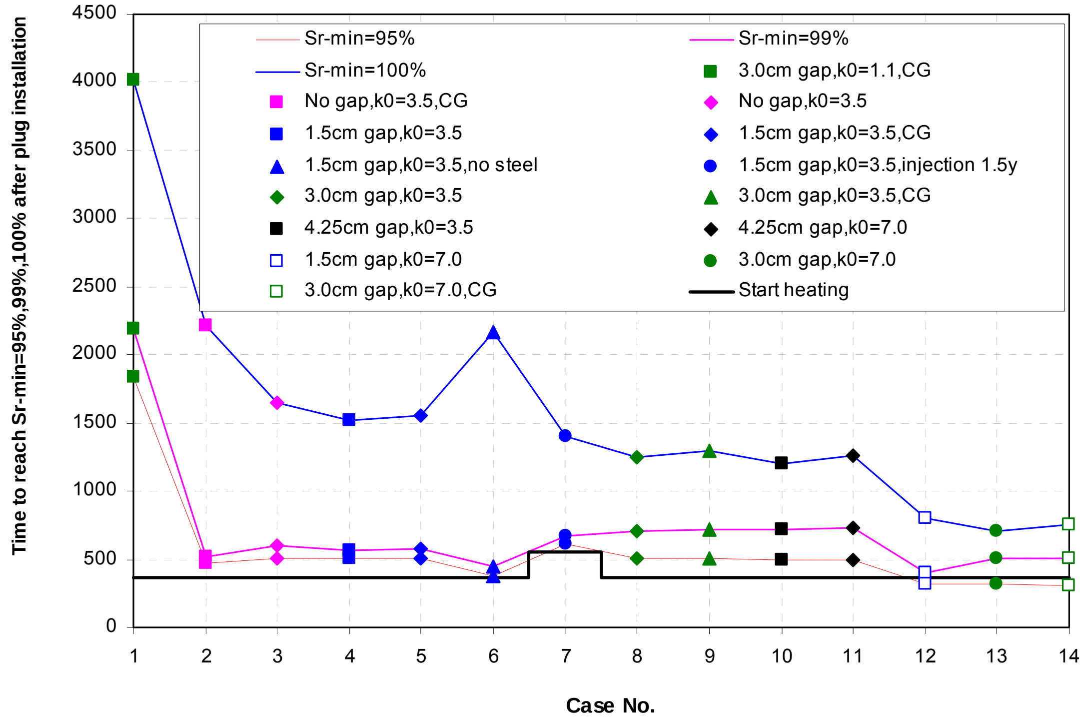


Figure 4-20 : Time to reach minimum saturation degree of 95%, 99% and 100%, dry density 1800 kg/m^3, in different cases

In order to check the impact of this not fully saturated state of the bentonite on the representative of PRACLAY heater test, radial profiles at mid-plan of heater (Figure 4-21) as well as the longitudinal profiles along the PRACLAY gallery wall (Figure 4-22 for cases with/without CG consideration) of the pore water pressure are drawn. It can be deduced that this not fully saturated state has little influence on the THM responses around the PRACLAY heater test, the longitudinal profile of pore pressure is mainly controlled by the presence of the connecting gallery.

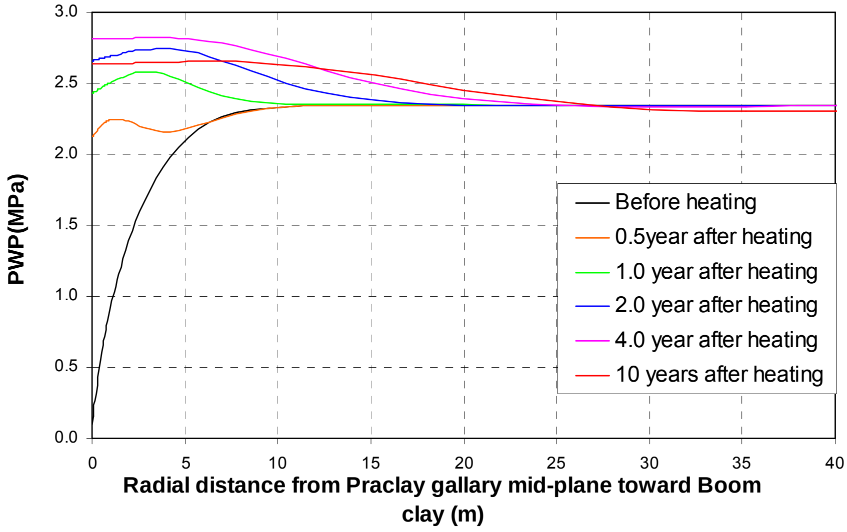


Figure 4-21 : Radial distribution of pore water pressure at the mid-plane of PRACLAY test (for case with 1.5 cm gap, dry density of 1800 kg/m^3, with CG consideration)

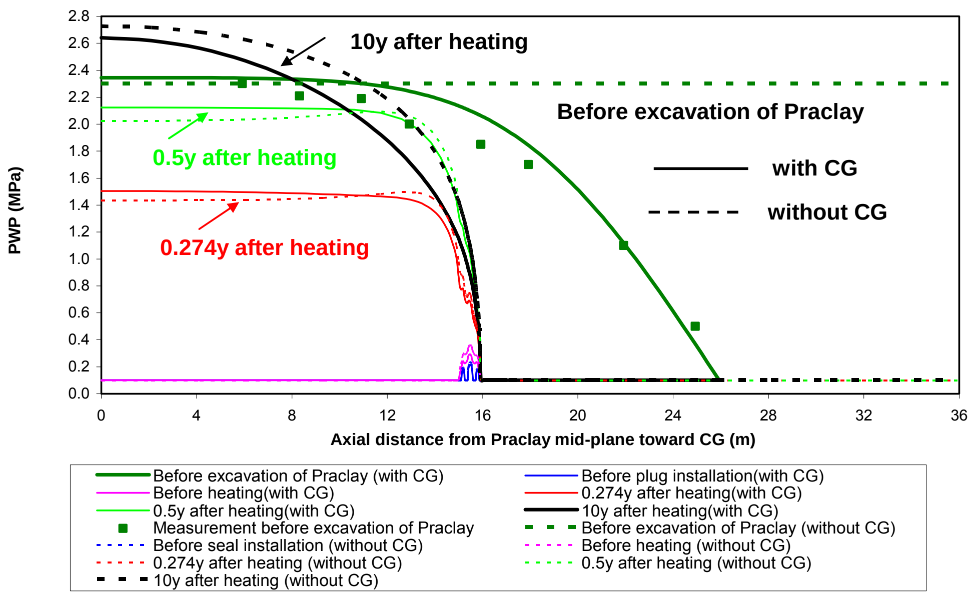


Figure 4-22 : Longitudinal profile of pore water pressure along inner surface of PRACLAY gallery (for case with 1.5cm gap, dry density of 1800kg/m3) - seal location at 15..16 m.

As a conclusion, **the scoping calculations provided information on the swelling pressure generation and saturation process of the bentonite seal**;

- It's clear that, for a given initial dry density, the technological void is the most important parameter to control the swelling pressure generation. Other 2D modelling with different initial dry density is still on-going. The final choice of the initial dry density will be taken when all simulation results are available.
- All numerical case studies revealed that a saturation degree of about 95 % can be reached before heating and full saturation before heating is unlikely. However, numerical simulation indicated that this has only a limited impact on the PRACLAY heater test.

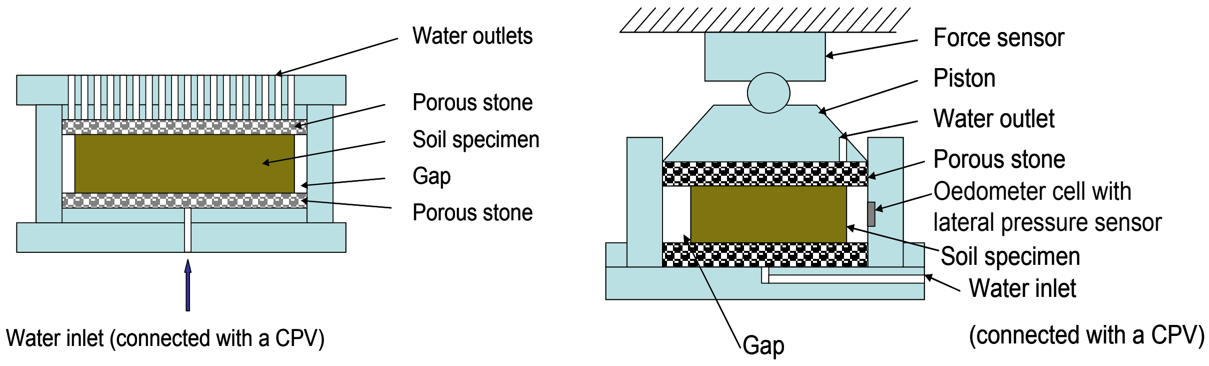
Nevertheless, the performance of the seal, especially at the interface Boom Clay/bentonite, needs to be checked before starting the heating. For example, gas build-up tests are foreseen for this purpose.

4.2.3 Complementary laboratory tests on bentonite MX-80, to evaluate hydraulic resistance of interface of compacted bentonite with Boom Clay

According to numerical scoping calculations, heating until 80°C will induce a pore pressure of the order of 3.0 MPa at the upstream side of the seal (heated part). However, since the downstream side of the seal is at atmospheric pressure, there will be a big gradient of pore pressure along the interface of Boom Clay/bentonite. In order to verify the effects of this water pressure on the performance of the annular seal system and more specifically on the hydraulic resistance of the interface of the bentonite and the host rock (Boom Clay), laboratory percolation tests at 20°C and 80°C were performed at the French CERMES institute. Compacted samples of MX-80 bentonite were used. The initial water content of the bentonite was 10%. The bentonite powder was sieved at 2 mm and statically compacted to a dry density of 1750 Kg/m^3.

Two devices were used. The first one (Figure 4-23a) was a percolation cell (50-mm inner diameter). The soil specimen (5 mm high) was confined between two porous stones. The diameter of the soil specimen was smaller than the inner diameter of the cell, defining a gap between the soil and the cell wall. The water inlet of the cell was connected to a controller of pressure/volume (CPV). The second device used (Figure 4-23b) was a constant-volume oedometer (50-mm inner diameter) equipped with vertical and horizontal stress sensors. The diameter of the soil specimen was also smaller than the inner diameter of the cell and a CPV was connected to the lower base of the cell. The gap between the soil specimen and the cell wall represented the technical gap existing, in real conditions, between the bentonite ring and the gallery wall (Boom Clay).

According to the numerical simulations, once the installation of the bentonite annular ring completed, depending on the initial dry density of the bentonite chosen, the hydration of the compacted bentonite by the Boom Clay pore water could lead to a saturation degree more than 95% after one year, fully saturation requires however very long time The saturation process will involve swelling that will fill the technical gap. In the laboratory test, the water injected in the cells first fills the gap and then induce swelling, hence limiting the water flow through the cell.



(a) (b)

Figure 4-23 : Percolation cell (a) and oedometer cell (b)

Once the compacted soil sample installed in the cell, water was injected by a CPV at a rate of 1 mm^3/s. The injected volume of water, the pressure monitored by the CPV, and the vertical and horizontal stresses were recorded (in the oedometer cell). The percolation tests were performed at two temperatures: 20°C and 80°C. To conduct the tests at 80°C, the cell was immersed in a temperature-controlled bath. Three gap thicknesses were used with values equal to 1.6, 1.8 and 2.0 mm respectively corresponding to specimen diameters D = 46.8, 46.4 and 46.0 mm (the inner cell diameter being 50 mm). That corresponds to the void percentages of 6.7, 7.6, and 8.5% (volume of void per initial volume of bentonite).

Three tests were performed in the oedometer cell (T19, T20 and T21). The tests T19 and T20 were undertaken on compacted specimens with gap values equal to 2.0 and 1.6 mm respectively. For test T21, the soil powder was deposited directly in the cell in order to obtain a very loose soil (ρ_d = 1.25 Mg/m^3). The gap thickness was then equal to zero.

The results of the percolation tests are presented in Figure 4-24. In Figure 4-24a, the changes of injected volume and the pressure monitored by the CPV are shown. It can be observed that the applied pressure quickly increased when water was injected. At t = 0.5 h, pressure abruptly decreased from 150 to 50 kPa and then increased until 25 000 kPa at t = 2 h. The sharp decrease of pressure during injection corresponds to hydraulic fracturing. Just after the beginning of the injection, water filled the gap and induced the swelling. As shown by Marcial et al. (2005), swelling occurs through the formation of a gel of bentonite that slows down the water flow, resulting in an increase of the water pressure needed to keep constant the injection rate. When the water pressure reached the hydraulic resistance of the gel in the gap, fracturing took place, resulting in a drastic pressure decrease. On the other hand, swelling of the soil mass also reduced the gap thickness, increasing the hydraulic resistance of the system. If the rate of the pressure increase is lower than the rate of increase in hydraulic resistance, the water pressure remains lower than the hydraulic resistance and thus there is no risk of fracturing. The results of test T04 (at 20 °C) confirmed that the final hydraulic resistance was higher than 25 000 kPa.

Figure 4-24b presents the results of the percolation tests performed at 80°C to check the effect of temperature on the hydraulic resistance of the interface with various gap thicknesses. It was observed that the hydraulic resistance was not reached at pressure of 5 MPa for the three gap thicknesses used.

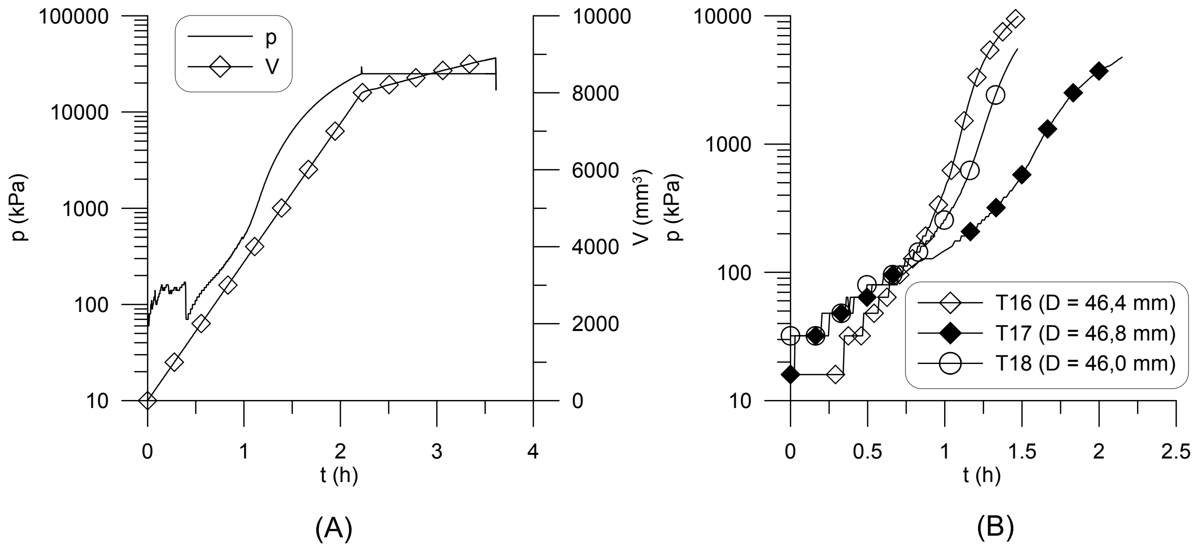


Figure 4-24 : Percolation tests. Changes of pressure and injected volume versus time. Test at 20°C (A: T04) and 80°C (B: T16, T17 and T18)

The results of test T19 for the first five hours (t = 0-5 h) are presented in Figure 4-25. After starting water injection, one observes that the water pressure started increasing after 1 h. The first fracturing was observed at t = 1 h with an abrupt pressure decrease from 100 kPa to 50 kPa. Starting from t = 2 h, various hydraulic fracturing occurred with an increase of the hydraulic resistance with time. For instance, at t = 4 h, a pressure of 1 MPa was required for fracturing.

Measures of vertical and horizontal stresses (σ_1 and σ_3 respectively) are also shown in Figure 4-25. The vertical stress increased quickly just after injection in relation with the swelling induced by putting the soil in contact with water. The vertical stress σ_1 reached 700 kPa after 1 h. The horizontal stress appeared to remain negligible until t = 1.5 h, a period during which the gap was progressively filled by the bentonite gel. From t = 1.5 h, the water pressure increases due to the complete filling of the gap by the bentonite gel, a filling that started to restraint the water flow, resulting in an increase of σ_3. Hydraulic fracturing can also be observed in the changes of both σ_3 and σ_1. In addition, the value of σ_3 at fracturing is equal to the water pressure value.

Injection was stopped at t = 7 h and subsequently restarted at t = 20 h. The corresponding results are presented in Figure 4-26. After this break, fracturing did not take place any longer even at a pressure as high as 10 MPa.

The results of test T20 are presented in Figure 4-27 (for t = 0 – 24 h) and Figure 4-28 (for t = 0 – 120 h). The soil was put in contact with water just after being installed but water injection at a rate of 1 mm^3/s only started at t = 16 h. Results show that the vertical stress (σ_1) quickly increased to reach 1500 kPa at t = 15 h while the horizontal stress remained negligible. Once injection was started (t = 16 h) water pressure, σ_1 and σ_3 increased until fracturing and abruptly decreased. The hydraulic resistance was close to 1 MPa. The injection was stopped during t = 24 – 90 h. After restarting water injection at t = 90 h, fracturing was no more observed even at a pressure of 10 MPa.

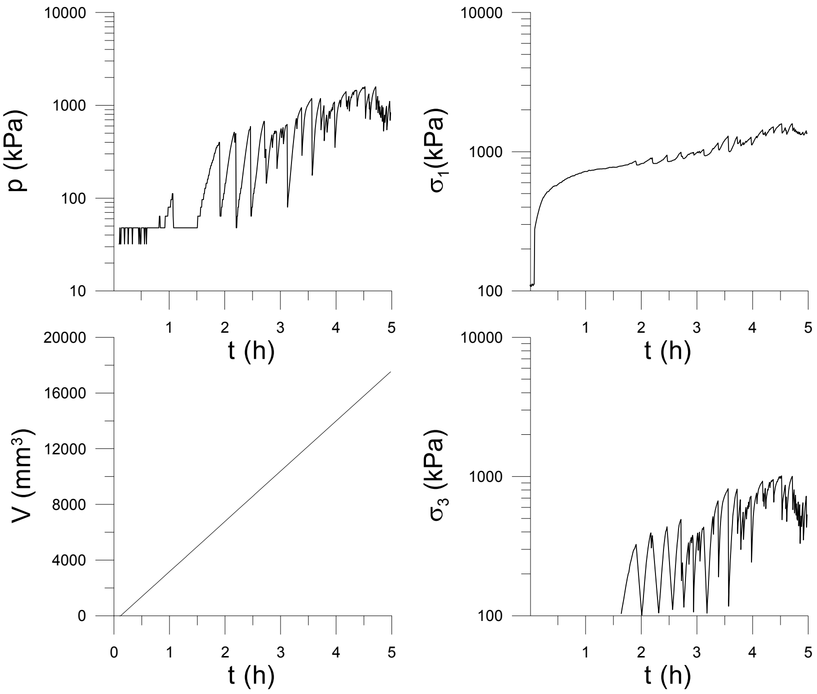


Figure 4-25 : Test T19. Changes of water pressure, injected volume, vertical and radial stresses versus time (for t = 0 – 5 h)

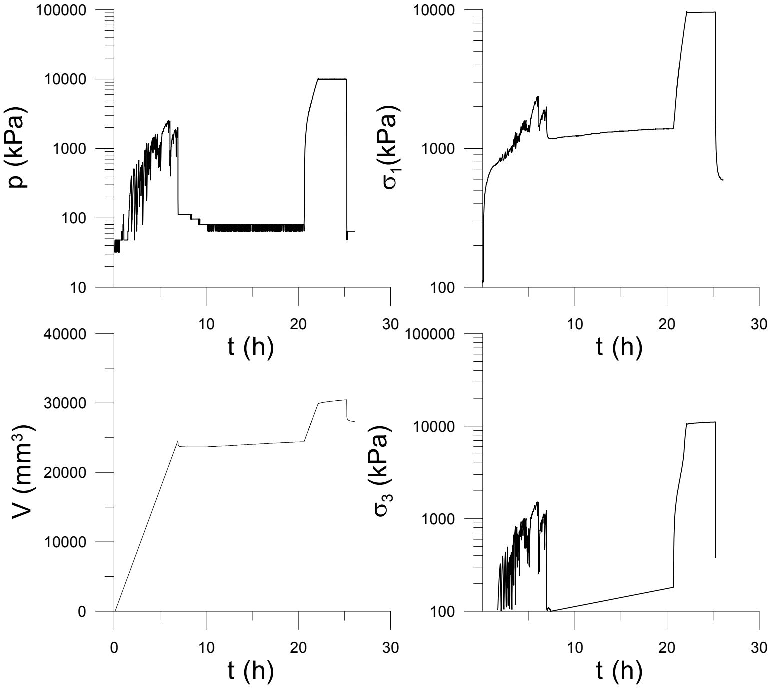


Figure 4-26 : Test T19. Changes of water pressure, injected volume, vertical and radial stresses versus time (for t = 0 – 30 h)

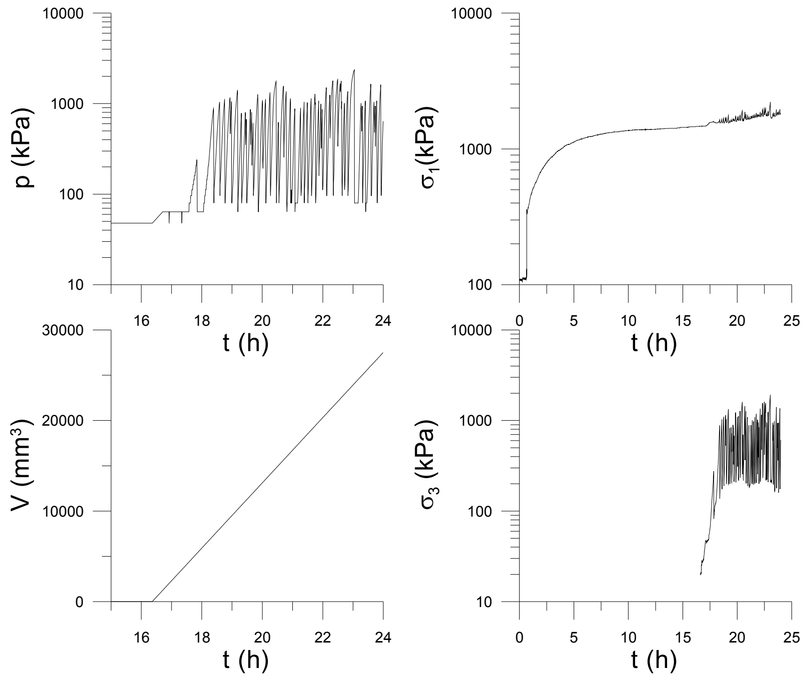


Figure 4-27 : Test T20. Changes of water pressure, injected volume, vertical and radial stresses versus time (for t = 0 – 24 h)

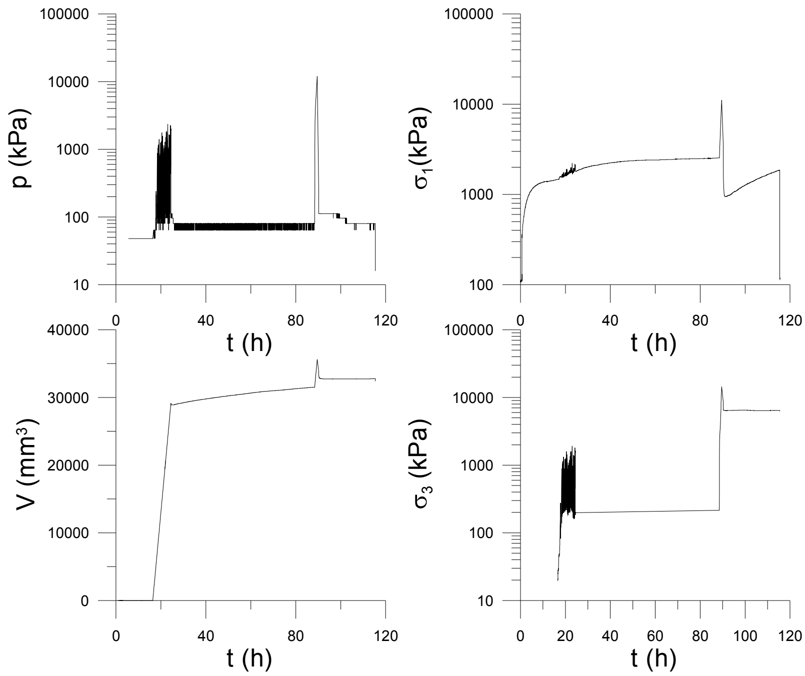


Figure 4-28 : Test T20. Changes of water pressure, injected volume, vertical and radial stresses versus time (for t = 0 – 120 h)

The results of test T21 are presented in Figure 4-29. Water pressure started to increase after 1 h of injection. After 6 h, the water pressure, σ_1 and σ_3 reached 10 MPa with no occurrence of fracturing.

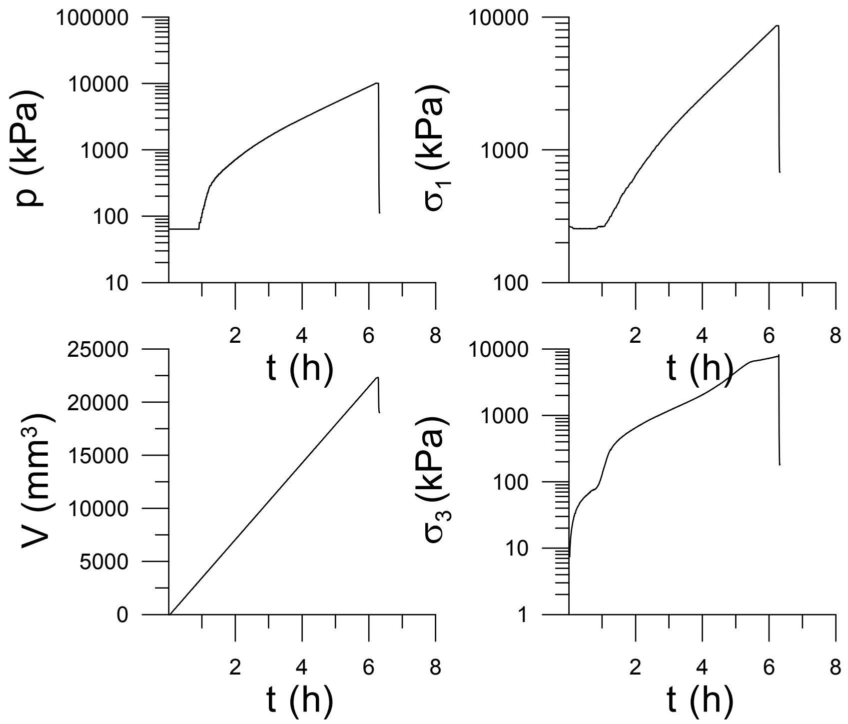


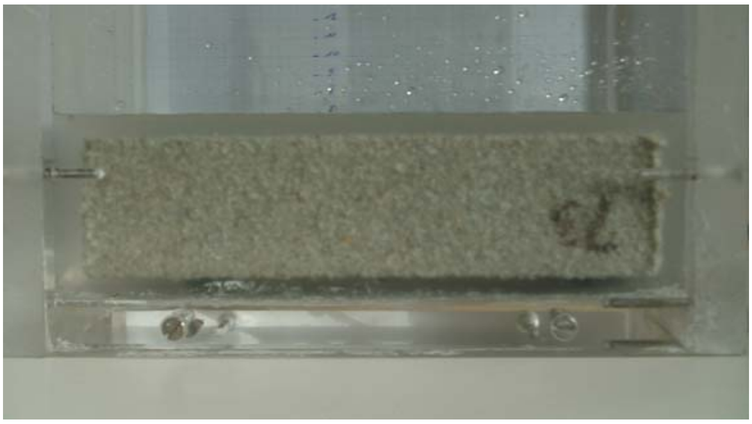
Figure 4-29 : Test T21: changes in water pressure, injected volume, vertical and radial stresses versus time

Thus, a novel simple system to investigate the effects of joints and technical gaps, which are unavoidable when installing compacted bentonite bricks in situ, was developed and used to investigate the resistance to hydraulic fracturing of discontinuities. Injection tests were performed in two different cells in which a cylindrical gap of controlled thickness was prepared between the soil specimen and the cell wall. When starting injection tests, water appeared to flow freely through the gap, keeping the water pressure equal to zero for some time. When the soil was put in contact with water, it swelled rapidly and reduced the gap, thus increasing the water injection pressure. The drop-down of pressure was observed during the first hours when the water injection pressure reached the hydraulic resistance of the soil/wall interface. Note that Marcial et al. (2006) [11] also observed that this breakthrough pressure increased with time. The evolution of the radial stress applied by the swelling soil on the inner wall of the cell evidenced a rapid swelling rate. The effect of the swelling pressure on the hydraulic resistance is fundamentally similar to that of the overburden pressure observed by Teachavorasinskun and Visethrattana (2006) [13] on compacted sand-bentonite mixture.

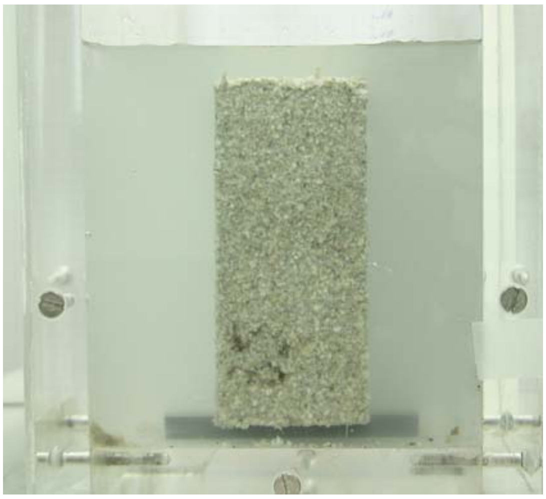
In the real situation of the seal/host rock interface, it is believed that the performance of a seal highly depends on the interface characteristic. In the present work, several tests have been carried out in a percolation cell with three gap thicknesses (2.0, 1.8, and 1.6 mm) and at two temperatures (20°C and 80°C). In addition, several tests have been performed in a oedometer cell at 20°C. All tests show that the hydraulic resistance of the soil/wall interface is higher than 5 MPa at completion of soil swelling, confirming the performance of the compacted bentonite seal under the foreseen hydraulic and thermal conditions.

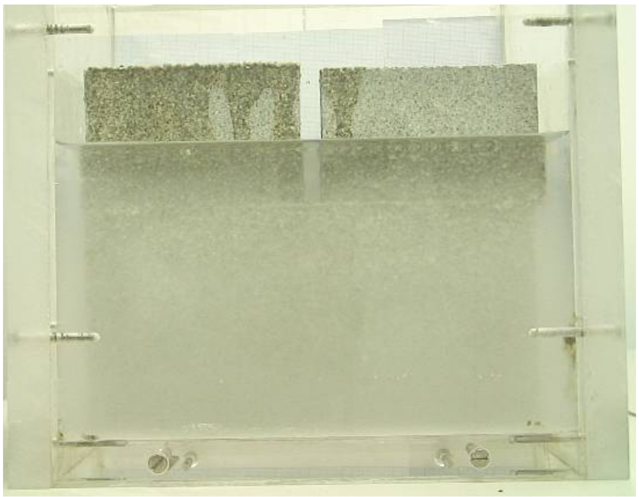
4.2.4 Complementary laboratory tests on bentonite MX-80, to evaluate hydration process on bentonite surfaces

The gaps existing inside the seal present the space allowing the bentonite to swell freely and potentially disintegrate when the artificial injection begins. In order to assess the hydration process on the bentonite surface where gaps are present, a small scale test set-up with a plexi-glass cell was made. The objective of the tests was to visualize the surface behaviour of the bentonite block upon hydration. The injection strategy should be adapted if the phenomenon of disintegration is observed, because this may lead to a non-homogeneous distribution of the bentonite and result in non-homogeneous swelling. This was the case in the OPHELIE mock-up test [12]; the inundation of the mock-up when staring injection led to the disintegration of the bentonite on the annular technological void and resulted in a non-homogeneous bentonite distribution between the upper and lower part of the mock-up. This phenomenon should be avoided in the PRACLAY seal test.



Test 1





Test 2 Test 3

Figure 4-30 : Evaluation of the hydration process on the bentonite surfaces

Three tests were performed with MX-80 bentonite blocks compacted at 1800 kg/m^3. The blocks were put in the cell, filled with water, and a free space (~1 cm) was left to allow the bentonite to swell freely. Different configurations were tested considering the compaction direction of the bentonite and different type of gaps:

- test 1: as shown in Figure 4-30, the bentonite is placed in such way that the compaction plan is horizontal
- test 2: the bentonite is placed in such way that the compaction plan is vertical
- test 3: a joint of 1 cm between two blocks was created observe the joint behaviour upon hydration

During the tests, pictures were made regularly (see Figure 4-30). The conclusion from these simple tests was that, for the pure bentonite blocks as compacted, there is no risk of disintegration and consequently, there is no need for a special procedure for injection.

4.3 Objectives of the test

The installation of the hydraulic seal fits in the framework of the PRACLAY In-Situ Experiment. The main purpose of this experiment is to investigate the impact of the thermal load of heat-generating waste on the Boom Clay host rock. To this extent, the gallery will be heated for 10 years over a length of 30 m. To assure undrained conditions during the thermal experiment, a hydraulic seal of 1 m will be installed. The necessity to have undrained conditions is explained further down in this section. An axial cross-section of the PRACLAY gallery, displaying the principal components of the In-Situ Experiment is shown in Figure 4-31.

The installation of the seal and its follow-up in time is a subtest within the In-Situ Experiment, referred to as the PRACLAY Seal Test. The PRACLAY Seal Test aims to demonstrate the possibility to hydraulically seal off a disposal gallery from the rest of the repository. Within the In-Situ Experiment, the seal is also necessary to assure undrained conditions for the thermal experiment.

The objectives within ESDRED were to design the steel support structure of the seal, to seek out the swelling material to be inserted in the annular gap created by the steel structure, and to perform the **in-situ** installation of the seal. The follow-up in time of the seal after its installation is not part of ESDRED.

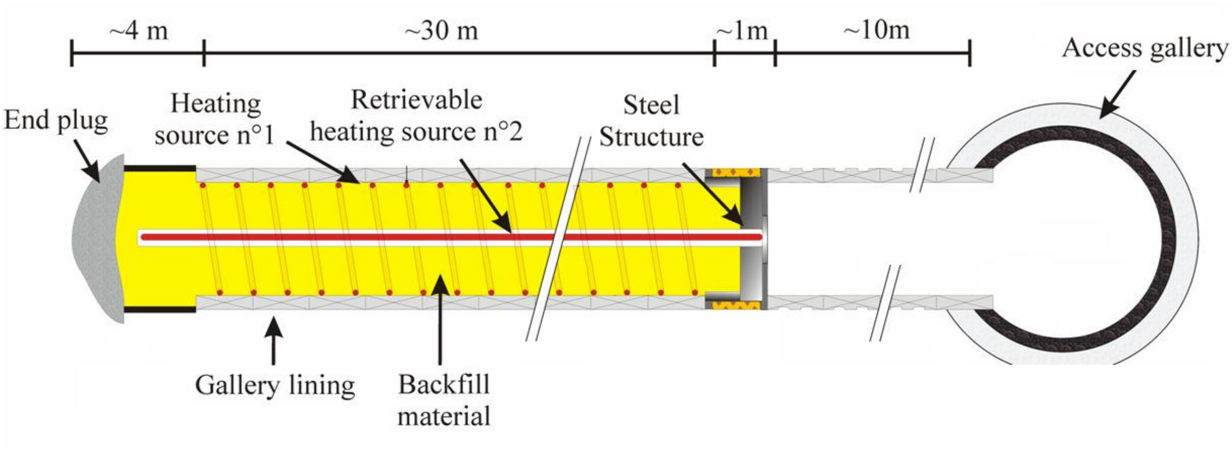


Figure 4-31 : PRACLAY gallery and main components of the In-Situ Experiment

Necessity to have undrained conditions in the PRACLAY experiment

It is necessary to assure undrained conditions for the thermal experiment. Indeed, the hydraulic initial and boundary conditions reached before the heating phase will condition the whole THM response in the Boom Clay both for a real disposal and for the PRACLAY Heater Experiment. As it is not possible to realize the experiments at the time scale of a disposal system, it was decided to carry out the PRACLAY experiments under most critical conditions in terms of THM responses of Boom Clay. The pressure build-up under heating is a crucial aspect. Indeed, an important issue is to verify that an excess pore pressure could not lead to the liquefaction of Boom Clay as a consequence of the decrease of effective stress. The higher the pore pressure increases, the higher the risk of liquefaction is, the more critical the THM response is considered to be. Numerical scoping calculations showed that the thermal induced pore pressure build-up is strongly controlled by the hydraulic boundary condition imposed to the heated gallery. As Figure 4-32 shows, the pore pressure build-up is much more pronounced in undrained conditions (impermeable boundary) than in drained conditions (permeable boundary). Hence, the undrained conditions are the most critical.

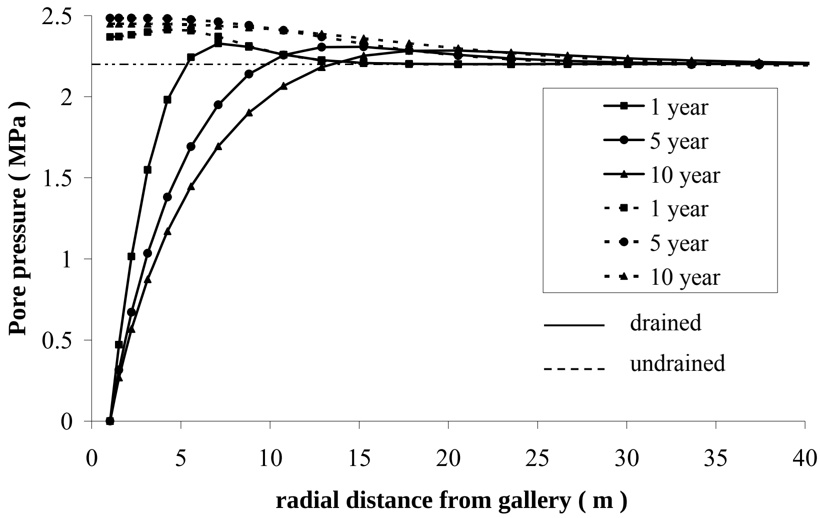


Figure 4-32 : Radial pore pressure profiles at mid plan of the heater for different heating time at different hydraulic boundary conditions

For the thermal experiment, the undrained conditions (impermeable boundary) will be realized by backfilling the heated part of the gallery with a fully saturated, high permeable material and by closing it with a horizontal seal. The importance of the seal in the realization of undrained conditions is indicated by Figure 4-5.

4.4 Execution of the test

The installation of the seal in the underground facility is foreseen for the second quarter of 2009. Note that the in-situ installation of the all components of the PRACLAY In-Situ Experiment is estimated to take about 10 months, starting from October 20th 2008. Note that this excludes the artificial hydration of the swelling material of the seal.

The delivery of the materials and the in-workshop construction of the seal will take about 7 months. Then the feasibility to install the seal in the gallery will be demonstrated by a pre-assembly on surface, for which 2 weeks are foreseen. If the pre-assembly is performed successfully, the seal will be transported to the site for its underground installation. The underground installation is estimated to take about 2 months and comprises the following phases:

- phase 0: introduction of the cylinder and the already assembled closing plates, stiffeners and the pipes inside the gallery (upstream side).
- phase 1: removal of the temporary part of the lining in the zone of the hydraulic seal.
- phase 2: installation of the ring flange of thickness 40 mm (upstream side). This flange is installed in four parts.
- phase 3: installation of the ring flange of thickness 100 mm (downstream side). This ring flange is also installed in four parts.
- phase 4: installation of the bentonite and installation of the instrumentation in the bentonite.
- phase 5: drawing of the cylinder to the bearing of the flange (thickness 100 mm) and welding it to the flange.
- phase 6: installation of the reductions and related flanges on openings I1, I2, I3 and I4.

After phase 6, the artificial hydration of the bentonite can start.

4.5 Post-test activities

After the installation of the seal, a monitoring programme will be conducted to assess the performance of the seal. In addition to this "black box" approach, a second objective is to understand the functioning of the seal by monitoring the bentonite evolution (hydration and associated swelling).

Thereto the following parameters will be measured:

- at the bentonite-host rock interface:
    1. pore water pressure
    2. total pressure at interface between host rock and the bentonite;
- inside the bentonite:
    1. porewater pressure
    2. permeability
    3. suction
    4. humidity
    5. moisture content
    6. swelling pressure
- at the bentonite-steel structure interface
    1. total pressure (by the bentonite) exerted on the steel support structure
    2. pore water pressure

In addition, several piezometer filters in the neighbourhood of the seal contribute to the monitoring of the seal performance.

4.6 Analysis of results and conclusions

With respect to the objectives within ESDRED (see Section 4.3), the design of the steel support structure of the seal and the selection of MX-80 as the swelling material have been achieved. The latter has included a literature study, a series of scoping calculations by aid of a computer code and laboratory testing focussed on a number of specific aspects related to the interface of the swelling material and the Boom Clay host rock.

The actual in-situ installation of the seal in the PRACLAY gallery remains to be done. Due to a rescheduling of works, this activity will fall outside of the contractual time framework of ESDRED (i.e. until February 1st 2009); it is now foreseen for the second quarter of 2009. However, to abide to its contractual obligations, EURIDICE will provide an update of the present report to include a description of the in-situ installation of the seal.

5 CONCLUSIONS

5.1.1 Résumé of level of success of the tests

The work performed within Module 1 Work Package 4 involved a full-scale grout injection backfill test on a 30 m long mockup of a disposal gallery, the in-situ demonstration of seal performance in a vertical borehole at the Mont Terri URL, and the design of the steel support structure and the selection of the swelling material for the PRACLAY seal at the Mol URL. The work has fulfilled the ESDRED contractual obligations, except for the actual in-situ installation of the PRACLAY seal. This activity is foreseen for the second quarter of 2009. The present report will then be updated to include a description of the installation of the seal. This opportunity may be used to provide also an update of the status of the seal performance testing at Mont Terri, which was anticipated from the beginning to continue beyond the contractual ESDRED time frame.

The grout injection backfill test was executed on April 8th 2008. From the results, it can be concluded that the application of the technique was essentially successful, but not fully. The injection was performed at a satisfactory rate, the annular gap was as good as completely filled and the mockup design proved to be very robust, but the grout did however fail to become hard as it should. Post-test evaluations nevertheless produced a plausible explanation for the failure of the grout to become hard, and a remedy was proposed. This remedy, a starting basis for future R&D, consists of reducing the W/C ratio to a maximum of 1.25 in combination with a limited increase of the superplasticizer content in the composition of the grout premix. The test was largely successful in providing a broad information basis which can be used for the next phases in the development of the grout backfill technology. The test allowed to monitor and analyze, on a 1/1 scale, the thermo-mechanical dynamics of the grout injection process, the actions performed by the operators and the involved operational safety hazards. Also, it gave a better insight in the logistical needs behind the backfill operation. A plausible explanation for the failure of the grout to become hard was derived and a remedy was proposed.

The operations at Mont Terri have so far been successful. The four test seals installed at Mont Terri are currently nearing a state of full saturation, more than 2 years after water injection was first started. These long times to reach saturation were predicted from a mockup simulation in the GRS laboratory in Braunschweig. After achieving full saturation, the gas break-through performance of the seals will be tested, but this is an activity that will, as not excluded at the beginning, fall outside of the contractual ESDRED time frame.

For the PRACLAY seal, at present, the design of the steel support structure of the seal and the selection of MX-80 as the swelling material have been achieved. The actual in-situ installation of the seal remains to be done. The installation it is now scheduled for the second quarter of 2009. No specific technical problems are anticipated at this stage.

5.1.2 Opportunities for further testing

The grout injection backfill test of April 8th 2008 has provided a broad information basis which can be used for used for the next phases in the development of the grout backfill technology. A plausible explanation for the failure of the grout to become hard was derived and a remedy was proposed. The logistical needs behind the backfill operation should be investigated from a multi-option perspective.

The Mont Terrri URL seal performance testing within ESDRED has indicated the suitability of clay/sand mixture sealing material to reconcile a low hydraulic conductivity with a high gas permeability (i.e. low gas entry pressure). The investigated material will thus remain in the focus of the GRS' future geotechnical

R&D on the clay disposal option. Since the investigated material is meant to be used in a HLW disposal configuration, its thermal properties also need to be determined. The GRS together with other Mont Terri partners and also German partners is therefore currently working on the development of project proposals which comprise besides the necessary laboratory determination of the thermal properties in-situ investigations of the thermal behaviour, especially in the early stage of a HLW repository.

The PRACLAY seal is an integral part of the PRACLAY In-Situ Experiment. After the installation of the seal, the swelling material will be artificially hydrated in order to achieve the necessary hydraulic seal off of the upstream part of the gallery, in which the 10-year long heater test will take place. The evolution of the swelling material and its interaction with the Boom Clay host rock will be monitoring throughout this whole time. The practicalities of the seal installation and the follow-up of the seal material will provide a useful information basis for the design of the actual repository seals and the prediction of their performance.

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7 SUMMARY OF ACRONYMS AND ABBREVIATIONS

ACRONYM or ABBREVIATION	EXPLANATION
1D, 2D, 3D	One-, two-, three-, dimensional
CG	Connecting Gallery (in the Mol URL)
CPV	Controller of Pressure / Volume
EC	European Commission
EDZ	Excavation Damaged Zone
HLW	High Level Waste
HPLC	High Performance Liquid Chromatography
MTRL	Mont Terri Rock Laboratory
NSF	Nuclear Spent Fuel
THM	Thermo-Hydro-Mechanic
URL	Underground Research Laboratory
W/C	Water / Cement ratio
WP	Work Package