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Deliverable 6 Module 1
Work Package 6

Module 1 Final Report

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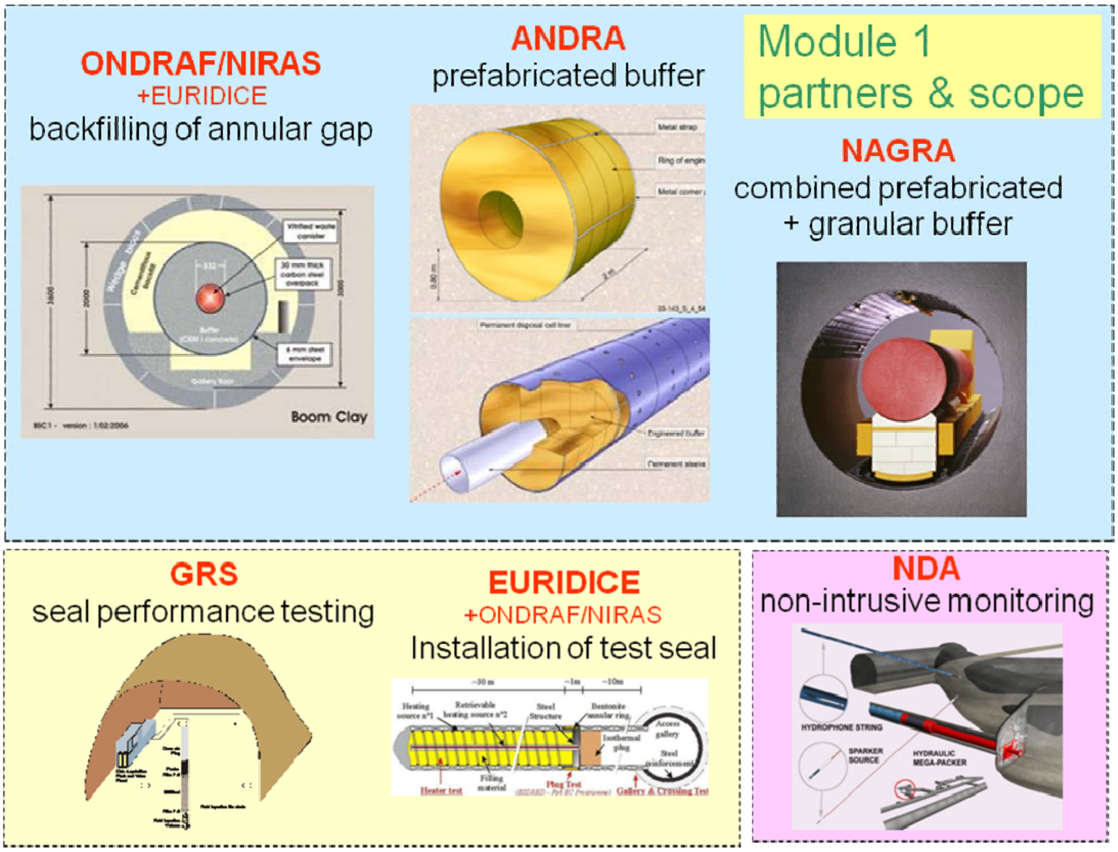
PUBLISHABLE EXECUTIVE SUMMARY

Work scope, background and objectives

ESDRED Module 1 was principally dedicated to the construction and/or emplacement, in a horizontal configuration, of the buffer around a disposed high-level waste package. In addition, Module 1 aimed to test the performance of seals (saturation rate and gas permeability) and certain seal installation aspects, and to advance the state-of-the-art of the application of non-intrusive monitoring techniques in geological repositories. The partner organizations working within Module 1 on specific subjects were: ONDRAF/NIRAS (Belgium), ANDRA (France), NAGRA (Switzerland), GRS (Germany), EURIDICE (Belgium) and the NDA (United Kingdom).



R&D projects before ESDRED Module 1 had already studied several bentonite materials and their conditioning to investigate their application as key materials in buffers, backfill or seals in geological repositories (e.g. RESEAL in Mol, or BOS in Grimsel). Most of these projects had been performed on a small or intermediate scale, and only a few addressed the emplacement techniques related to these components. The demonstration testing at full scale that had been performed was essentially limited to the vertical disposal configuration (e.g. work by SKB related to the KBS-3V design). From studying these projects it was clear that the horizontal configuration would pose specific challenges that had not been sufficiently addressed. At the same time, the horizontal configuration was getting increased consideration in disposal concepts (reference or alternative) of a number of EU countries. Module 1 was therefore in the first place set up to advance the state-of-the-art of the technology relating to the construction of the buffer or the backfill around a horizontally disposed high-level waste package.

The work involved the following more specific operational objectives:

- Backfilling of horizontal annular gap:
  - Grout backfilling: to test, first on a 2/3rd scale mockup and then on a 30 m long full scale mockup, whether the annular gap can be filled within a time frame during which the fluidity of the grout can normally be guaranteed (i.e. about 5 hours) and to achieve a quasi complete filling of the void with homogeneous backfill material. The composition of the specific grout is predominantly determined by long-term phenomenological requirements.
  - Dry granular materials: to test on a 2/3rd scale mockup whether the annular gap can be filled, using the dry-gun technique, at a linear pace that would allow application in the actual repository (i.e. faster than 1 m/h) and to achieve a quasi complete filling of the void with homogeneous backfill material. The work involved a pre-selection of the most promising dry granular materials, while focusing on the technological aspects. Robust projection equipment was designed specifically for operating under the mechanically harsh conditions invoked in the annular gap environment by the dry-gun technique.
- Prefabricated buffer configuration:
  - The specific objective was to fabricate 10 rings and 2 discs of 2.3 m outer diameter, with 0.8 m diameter inner opening and of 0.5 m thickness. The equipment needed for handling, for assembly in sets of 4, for packaging, for transportation and for storage of the rings once they had been pressed in a mould also needed to be designed, fabricated and tested.
- Granular buffer in combination with prefabricated blocks:
  - The objective was to select and test a number of mixtures of different granule size of MX-80 bentonite derived by computer modeling, to fabricate these mixtures and to use these to perform backfill testing on a 2/3rd scale mockup using auger emplacement technology, with the operational target of obtaining a dry density of 1500 kg/m3.

The general objective related to the low pressure gas entry/break-through seal testing was to check whether the borehole seals would behave as predicted from laboratory experiments. The operational objective was to see whether the entry/break-through pressure during gas injection would be below 2 MPa (a Mont Terri specific value).

Both the seal installation testing (PRACLAY) and the non-intrusive monitoring development had the general objective to advance the associated state-of-the art technological know-how. Specific operational targets were less relevant.

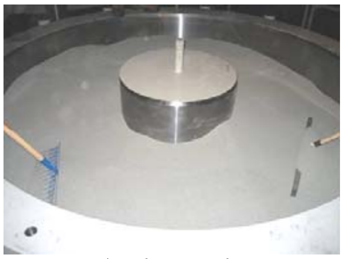
Achievements

At the end of the contractual project time frame, ESDRED Module 1 has achieved all of its objectives. There is one experiment (PRACLAY seal) that is awaiting mid-2009 for minor contractual work to be finalized and there are two experiments (SB seals and non-intrusive monitoring) that can expect an interesting contribution from additional work that will be performed in 2009 independent of the ESDRED Project. Results on non-intrusive monitoring will be fully reported as part of the MoDeRn Project while the SB experiment will generate a stand alone public document.

ANDRA has succeeded in the cold compaction of a MX-80 bentonite / quartz sand mixture prepared as a powder, to obtain the prefabricated buffer rings described in their *Dossier 2005* report to the French Government. ANDRA has also successfully tested the handling of these buffer rings and their rigidity.

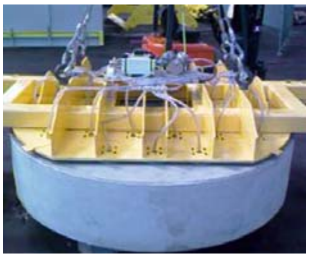
Mould being commissioned (Creusot)

Mould under the press (Issoire)



Bentonite/sand mixture being put in mould

Ring just after stripping from the mould



Lifting a disc by suction cup handling device

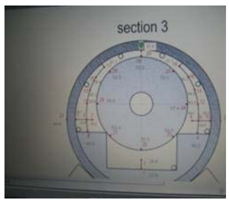
Deposition by lifting yoke of 4 pre-assembled rings on transport container lower part

ONDRAF/NIRAS has demonstrated the feasibility of two different emplacement techniques for backfilling the annular void around a horizontally disposed high level waste package: (1) projection of a dry granular material, for which sand, cement, bentonite and mixtures thereof were used, (2) injection of a custom made high pH grout designed to have the required thermal, chemical and physical characteristics. Both emplacement techniques have been tested successfully on 2/3rd-scale mockups. The grout injection technique was also tested on a full scale mockup of 30 m in length. Again, the feasibility of the injection technique was demonstrated, but it was also concluded that the water/cement (W/C) ratio of the specific grout will need to be reduced in the next phases of the development process, to ensure that the grout becomes hard shortly after injection. The backfill tests have provided a broad knowledge basis for this further development.

Backfill test with pure MX-80 – after the test:

- heavy duty for the projection vehicle
- annular gap (right side)
- Look in borehole at location of backfill

Grout mixing (3 mixers in parallel)

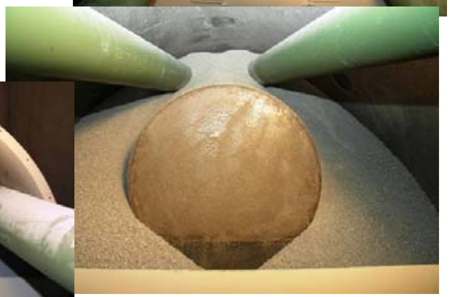


Direct verification of characteristics of each batch

NAGRA, using auger technology and a reduced-scale steel model of a horizontal disposal drift with a waste container placed on a cradle of prefabricated bentonite blocks, has tested the emplacement of a range of bimodal mixtures of granular bentonite. NAGRA succeeded in achieving the desired dry density of the emplaced buffer material.

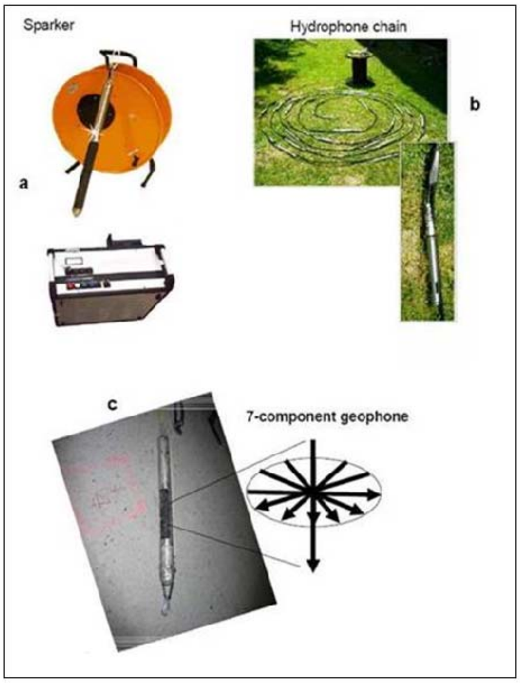
Buffer emplacement test (NAGRA), executed July 2006

Gradual filling of the gap during the test (pictures from top to bottom)



Since October 2005 GRS has been running (continuously and satisfactorily) in-situ performance tests on four seals of different clay/sand composition, in boreholes drilled at the Mont Terri URL. The results obtained so far from these in-situ tests, and the results obtained from the preceding (but still ongoing) laboratory mockup tests, confirm the advantageous sealing properties of moderately compacted clay/sand mixtures. Such advantageous sealing properties were previously determined on small samples under ideal conditions in the laboratory. However the seal saturation rates (in the mockup and in-situ) are much slower than predicted by computer models, based on earlier laboratory work. Consequently the gas injection tests in the laboratory mockup were significantly delayed and the in-situ entry/break-through gas injection tests will now most probably be executed around mid-2009. Since the beginning of ESDRED it has always been recognized that the duration of the in-situ tests could easily extend beyond the contractual end date of the Project. However it has come as a surprise that even in the laboratory mockup tests (which should have been completed long ago) the gas break-through is only now imminent. The work completed and the results already obtained have considerably advanced the knowledge base regarding moderately compacted bentonite/sand seals in clay host rock.

NDA has successfully conducting a development program to advance the knowledge regarding non-intrusive monitoring based on seismic tomography. A series of measurement campaigns have been performed around the HG-A tunnel in the Mont Terri URL. To interpret the information provided by the seismic echoes, an anisotropic model of the clay test environment has been developed and an associated full wave inversion code is being developed, in cooperation with the Swiss Federal Institute of Technology (ETH Zurich) as part of a PhD programme. Due to a rescheduling of the HG-A experiment, the last campaign is now anticipated to take place in mid-2009. The performance of this final test campaign, and the finalization of the wave inversion code, will contribute to the already gathered knowledge base.



Typical equipment

Installing the P-wave hydrophone stinger

Geophones installed on wall of empty micro-tunnel

EURIDICE have prepared the design of the PRACLAY seal steel support structure and have selected MX-80 as the swelling material to be used. The latter selection has involved a literature study, a series of scoping calculations by aid of a computer code and laboratory testing (e.g. at the CERMES institute) focusing on a number of specific aspects related to the interaction 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 completed. Due to a rescheduling of works, the in-situ installation of the PRACLAY seal will fall beyond the contractual end date of ESDRED. The installation is now foreseen for the second quarter of 2009. The work by EURIDICE, especially the actual in-situ implementation, will have advanced the phenomenological and technical knowledge base related to the construction of a hydraulic seal in a disposal gallery.

Recommendations / perspectives for the future

The work performed by ANDRA regarding prefabricated buffer rings has delivered a complete product. In view of the fact that in the meantime the French HLW disposal concept has been changed and no longer includes these rings, it would not be justified to state that further development is now required. The work by ANDRA has nevertheless resulted in an off-the-shelf solution that is still useful for other disposal programs, outside of France, as well as for the hypothetical French direct disposal program for spent fuel. Furthermore it provides a better basis for comparing this technical option with other alternatives. The acquired technological know-how could also be used for the fabrication of large-dimension compacted sealing blocks.

Regarding the non-prefabricated options to emplace the buffer/backfill, the work by O/N and NAGRA should be followed by a further fine-tuning of the composition of the material. An important boundary condition, which has until now been neglected in many programs is the understanding of the logistical needs behind the buffer/backfill emplacement. It is therefore strongly recommended to reserve an important part of future development efforts to the study of these logistical needs and the development of equipment to satisfy these.

Regarding the design and construction of seals, it is clear that a lot of R&D work still needs to be done especially regarding the installation techniques. The understanding of the saturation process as well as the applicable computational models both need to be improved in order to achieve better predictions of saturation times. Thanks to its sand content the SB sealing material shows a higher thermal conductivity in addition to its advantageous hydraulic properties. Favorable near-field conditions will therefore take place in a HLW repository in a clay formation when using the SB sealing material rather than the highly compacted 100% bentonite buffers considered in many other disposal concepts. The continuation of R&D regarding the suitability of the SB sealing material as an alternative will therefore remain the focus of future GRS geotechnical R&D related to the clay option. Working at full scale and in close collaboration with industrial companies which master the state-of-the-art in underground construction technologies, will enable waste management organizations to get a better understanding of the technological challenges involved.

Regarding non-intrusive monitoring, it is recommended that more R&D should be devoted to further improving the usefulness of seismic tomography. Particularly, the linking of the tomogram and waveform data to specific processes should receive dedicated attention. Moreover, to guide technology development, further work should be undertaken to identify monitoring objectives, strategies and decision making processes in order to improve the understanding of requirements on monitoring techniques.

1 INTRODUCTION

1.1 Summary of ESDRED project

The Integrated Project known as ESDRED (Engineering Studies and Demonstrations of Repository Designs) has been a joint research and development effort by major national radioactive waste management agencies (or subsidiaries of those agencies) and by research organizations. ESDRED was coordinated by the French National Radioactive Waste Management Agency (ANDRA) and was part of the European Union's 6th Euratom Framework Programme for Nuclear Research and Training. The five year Project started with a total budget of EURO 18.4 million, of which 7.3 million was provided by the EU's Framework Programme. Many of the participants elected to do more, or more elaborate, work than originally envisaged so that a conservative estimate of the total final expenditure (including other increased costs) is 23 million Euros.

The 13 participants (Contractors) in this project, from 9 European countries, were:

Radioactive Waste Management Agencies:	**Technological R&D Organizations:**
ANDRA, France	AITEMIN, Spain
ENRESA, Spain	CSIC, Spain
NAGRA, Switzerland	DBE TECHNOLOGY, Germany
NDA (Originally NIREX), United Kingdom	ESV EURIDICE EIG, Belgium
ONDRAF/NIRAS, Belgium	GRS, Germany
POSIVA, Finland	NRG, the Netherlands
SKB, Sweden	

ESDRED was mainly focused on technology issues and had **THREE MAIN OBJECTIVES**.

The **FIRST ESDRED OBJECTIVE** was to demonstrate, at an industrial scale, the technical feasibility of some very specific activities related to the construction, operation and closure of a deep geological repository for high level radioactive waste. This part of the work was organized inside four (4) Technical Modules (and numerous work packages) and essentially involved the conception, design, fabrication and demonstration (and further evaluation) of specific equipment or products for which relevant proven industrial counterparts (mainly in the nuclear and mining industry) do not exist today. Execution of the work was often by third party sub-contractors (especially the detailed design, fabrication and testing of new equipment) although, depending on the participant, some of the work was done in-house. Each of the four technical Modules involved from 3 to 7 participants thus always bringing the know-how and experience from several different national disposal concepts to the work. The programmes within these Technical Modules are provided below.

- Within **Module # 1, Buffer Construction Technologies for Horizontal Disposal Concepts,** certain participants were able to successfully design the necessary formulation and thereafter produce 4 ton bentonite rings to be used as an engineered barrier. Other participants demonstrated backfilling of the annular gap between a waste canister and the disposal drift wall using a variety of wet and dry products. Still others developed the product and the technique for backfilling disposal drifts with granular bentonite. The evolution over time and the performance of bentonite based seals, particularly in relation to gas permeability, was also assessed and is in fact on-going beyond ESDRED. Finally non- intrusive monitoring techniques based on seismology were also developed and demonstrated paving the way for additional experiments and cooperation between some of the partners beyond the end of the ESDRED Project.

- In **Module # 2,** the 2 main participants were able to design, fabricate and demonstrate the equipment needed for the **Transfer and Emplacement of Waste Canisters** weighing between 2 and 5.2 tons, in both horizontal and vertical disposal boreholes. A critical review type desk study related to retrievability of emplaced canisters was produced by a third partner.

- **Heavy Load Emplacement Technology** for horizontal disposal concepts was the only focus of **Module # 3.** In this Module two machines were successfully produced, each capable of emplacing 43 to 45 ton waste canisters in bored disposal tunnels while maintaining only a very small annular gap between the canister and the walls of the tunnel. One machine was based on water cushion technology while the other used air cushions. The latter machine was subsequently adapted to demonstrate the emplacement of sets of 4 pre-assembled bentonite rings (produced in Module 1), weighing 17 tons.

- The work in **Module # 4, Temporary Sealing (using low pH cement) Technology,** consisted first of designing a low pH cement formulation and then of preparing several concrete designs suitable for the construction of sealing plugs and for rock support using shotcrete techniques. A short plug was constructed at Äspö in Sweden and it was very quickly loaded to failure i.e. slippage by applying water pressure to one face. A second, much longer full scale plug was subsequently constructed at Grimsel test site in Switzerland. It was loaded using the swelling pressure created by bentonite blocks which were artificially hydrated. At time of writing the long plug had not started to slip. As the saturation of the bentonite is taking longer than expected the partners involved agreed to continue with the saturation of the bentonite blocks and the related data monitoring. The results of the test will be followed under the EURATOM's 7th Framework Programme, **MoDeRn** Project.

A **SECOND** and equally important **ESDRED OBJECTIVE** was to promote a shared European vision in the field of radioactive waste disposal technology. This was accomplished through the **INTEGRATION** process, which is the essence of **Module 6** and which is one of the key objectives that identify EURATOM's 6th Framework Programme. Among other things **INTEGRATION** resulted from working together, from sharing information, from comparing input data and functional requirements, from learning about one another's difficulties, from developing common or similar tender documents and bidder lists, from jointly developing courses and workshops and from coordinating demonstration activities whenever possible. Generally at least 2 **INTEGRATION** meetings were convened annually so that all ESDRED participants were updated on the progress of the work in all the Modules. Whenever practical these meetings were combined with the demonstration of a particular piece of new equipment, process or construction.

The **THIRD ESDRED OBJECTIVE** was entirely focused on training and communication which is the essence of the work in **Module 5** of the Project. Over the life of the project the participants wrote articles, presented technical papers at international conferences, held workshops, produced videos, developed and presented university lectures. The Project finished up by organizing an international conference on the operational aspects of deep geological disposal in June 2008 and by contributing significantly to the EURADWASTE '08 Conference in Luxembourg/Bure in October 2008. A web site (www.esdred.info) was created and maintained over the life of the project with more than 16 000 visitors by Q3 2008. This site will be kept on line until 2010.

1.2 Cold compaction of bentonite buffer rings (by ANDRA)

1.2.1 Background

The Law of December 1991 governing ANDRA's activities called for studies conducted over a 15-year period, including the evaluation of disposal options in deep geological formations. The results of these studies are presented in a report called "Dossier 2005". In the meantime, in 1999 ANDRA was granted a license to construct and operate a URL in the Callovo-Oxfordian formation (a type of clay rock called Argillites) at Bure (Meuse/Haute-Marne site).

The geological repository layout design developed by ANDRA (for the Dossier 2005) is based on the technical and scientific data coming from this site, and more particularly from the data and characteristics collected on the host rock (located at a depth of 500m with a thickness of 110m and a regular dip of 1° to 1.5° to the North West).

The repository layout is designed to accommodate various categories of waste packages, including HLW vitrified canisters and potentially un-reprocessed spent fuel canisters. The disposal concepts vary with the type and nature of waste packages. Some concepts call for the need of buffer material and more generally speaking for the use of an engineered barrier based on bentonite type material. The R&D work undertaken by ANDRA on bentonite buffer rings within the frame of the ESDRED Module 1 programme are thus conducted in line with the objectives and content of the Dossier 2005.

Bentonite buffer is considered to be placed around 2 types of canisters:

- The vitrified HLW or type C waste, which comes from AREVA, as a by-product of spent fuel recycling. This package is composed of a vitrified material encased into a stainless steel envelope (thus forming the primary package) which is itself surrounded by a 5cm thick carbon steel overpack (thus forming a 2t disposal package).
- The spent fuel package, which comes from spent fuel assemblies emplaced into a cast iron insert (thus forming the 43t SF disposal package).

Vitrified waste canisters and spent fuel canisters are emplaced in horizontal drifts (also called disposal cells), approximately 40m long. Those cells are of the same type for C and SF canisters, only cell diameters vary with the canister diameters, but remain around 2.5 – 3.2m. The related disposal concept is shown below in **Figure 1**.

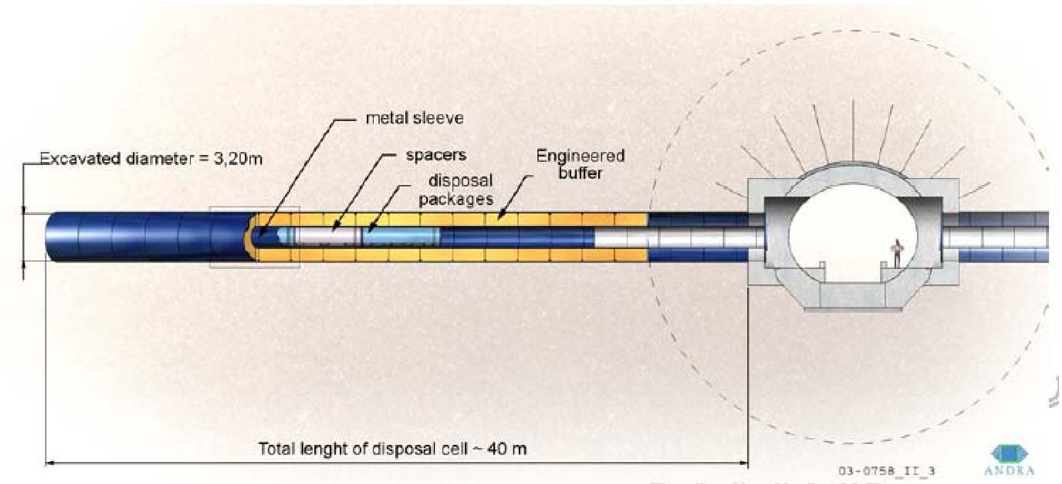


Figure 1: Cross-section of disposal concept for vitrified HLW and spent fuel

Each disposal cell is composed of (from the exterior to the interior – see **Figure 3**):

- a steel liner, approximately 30 mm thick, perforated with holes in order to allow bentonite resaturation with water coming from the host rock,
- an annular layer of bentonite, 800 mm thick (in radius) composed of cold-compacted rings,
- a steel sleeve, made of carbon steel, 25 to 40 mm thick, which holds 3 to 22 disposal packages.

According to the current concept, a disposal cell construction involves the following sequence:

- The disposal cell is excavated with a micro-tunnel boring machine (TBM),
- A perforated steel liner is pushed forward progressively as the TBM progresses,
- Once the disposal cell is totally excavated and lined, then the buffer material is emplaced (in sets of 4 pre-assembled bentonite rings) inside the liner (the associated emplacement method using air cushion technology is developed in details in Module 3 of ESDRED),
- The cell construction finishes with the introduction (inside the bentonite rings) of a steel casing (also called the permanent sleeve) which will receive later the disposal packages (C type or SF).

A cross-section (see **Figure 2**) showing the waste canister located in a C type disposal cell shows the theoretical annular clearances which are deemed necessary for an easy emplacement of all the objects.

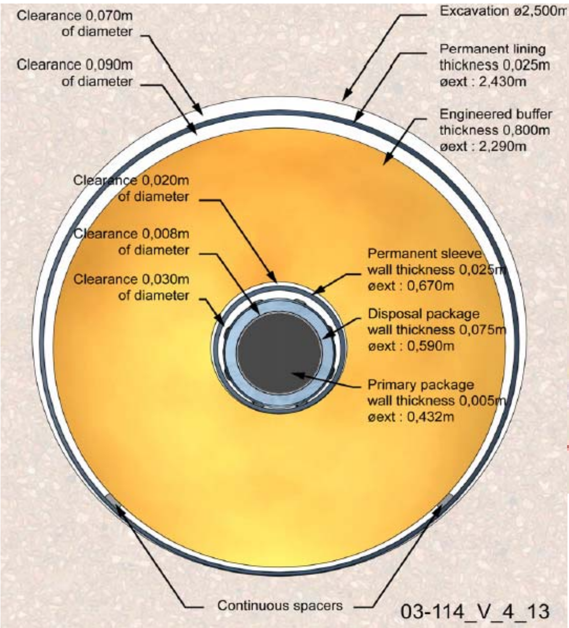


Figure 2: Cross-section of a vitrified HLW disposal cell with bentonite buffer

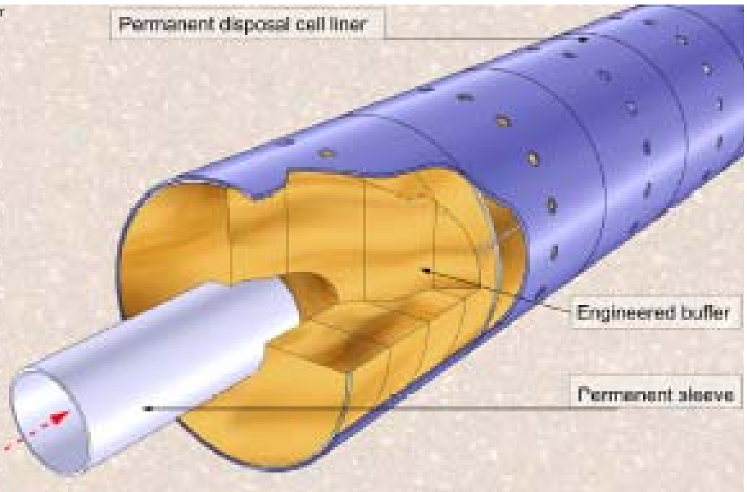


Figure 3: Main components of a disposal cell for C type & SF packages

1.2.2 Objectives

The objectives of ANDRA within Module1 and in integration with those of Module 3 of the ESDRED Project were to fabricate, for demonstration purposes, a full scale mockup of a horizontal disposal cell, and more specifically, to build and emplace the buffer material inside the perforated liner.

Fabrication of an engineered buffer (made of bentonite ring) was then the main objective of Module 1. Although emplacement of buffer rings is not a part of Module 1 (it is part of Module 3), the design of buffer rings was integrated as an input technical data to develop methods for their transportation and later emplacement (in sets of 4 pre-assembled rings) inside the liner and vice versa (their was a natural technical and time integration between the ESDRED Module 1 and ESDRED Module 3 design and operational programmes to make it possible).

A more detailed description of the general objectives of ANDRA within ESDRED Module 1 is given below. They are compatible with the development (within ESDRED Module 3) of a handling method suitable for emplacement of sets of buffer rings into the disposal cells:

- *to confirm, based on theoretical mechanical tolerances (the gap between the ID of the buffer ring central hole and the OD of the central inner sleeve), the effective clearance needed between the inner sleeve and the buffer ring central hole,*
- *to confirm, based on theoretical mechanical tolerances (buffer rings, emplacement method, drift liner), the effective clearance needed around the outside of the buffer rings,*
- *to confirm the composition of the buffer mixture (based on fabrication constraints and on functional requirements): bentonite content, sand content, dry density, moisture content, etc.*
- *to get all relevant information on finalised buffer material: mechanical strength, thermal conductivity, hydraulic conductivity, swelling characteristics, etc…*
- *to build real buffer rings and quantify fabrication tolerances,*
- *to get practical knowledge on buffer handling (individual rings and set of rings),*
- *to select and test a method for assembling the rings in sets of 4 rings,*
- *to design and check protection packaging for long term preservation, crating and shipping,*
- *to get a "show case", in other terms a "demonstrator" at an industrial scale (fabrication and assembling of buffer rings to be filmed and fully documented),*
- *to deliver a set of pre-assembled buffer rings to the heavy load transportation demonstrator of Module 3 for emplacement into a disposal cell perforated liner mockup.*

The buffer material **(a mixture of 70% MX-80 bentonite & 30% quartz sand**), after cold compaction, had to fulfil the following petro-physical properties (deemed necessary to cope with long term disposal phenomenology):

- *Thermal conductivity of the buffer*:
  - before resaturation : **1.2 W/m °C,**
  - after resaturation and swelling: **1.5 W/m °C,**
- *Hydraulic conductivity of the buffer*: **10^{-12} m/s** (target value). This value applies to the buffer material after swelling and void filling of the annular gaps (see cross-section in **Figure 2**). It does not apply to the prefabricated ring itself, but only to the engineered barrier after evolution with time in the repository conditions.
- *Gas permeability and conductivity of the buffer*: Gas permeability must be as high as possible; there is no threshold value.
- *Density*: **1.92 10^3 kg/m^3** after resaturation and swelling,
- *Maximum swelling pressure* should not exceed **7 MPa** (excluding pore pressure) in order not to damage the surrounding host rock,
- *UCS value*: **9 MPa;** this value is deemed acceptable for a disc or a ring installed on supporting rails fixed on the perforated liner invert,
- *Tensile strength*: about **1 MPa**.

Each ring has the following pre-defined dimensions and tolerances:

- 50 cm thickness,
- 2.27/2.28 m (+/- 5%) external diameter,
- 0.673/0.675 m (+/- 5%) internal diameter

Besides, assembling the rings in set of 4 units requires that rings be homogeneous in terms of shape, before being assembled and later lifted (handled) as one load. **Figure 4** below shows the tolerances allocated.

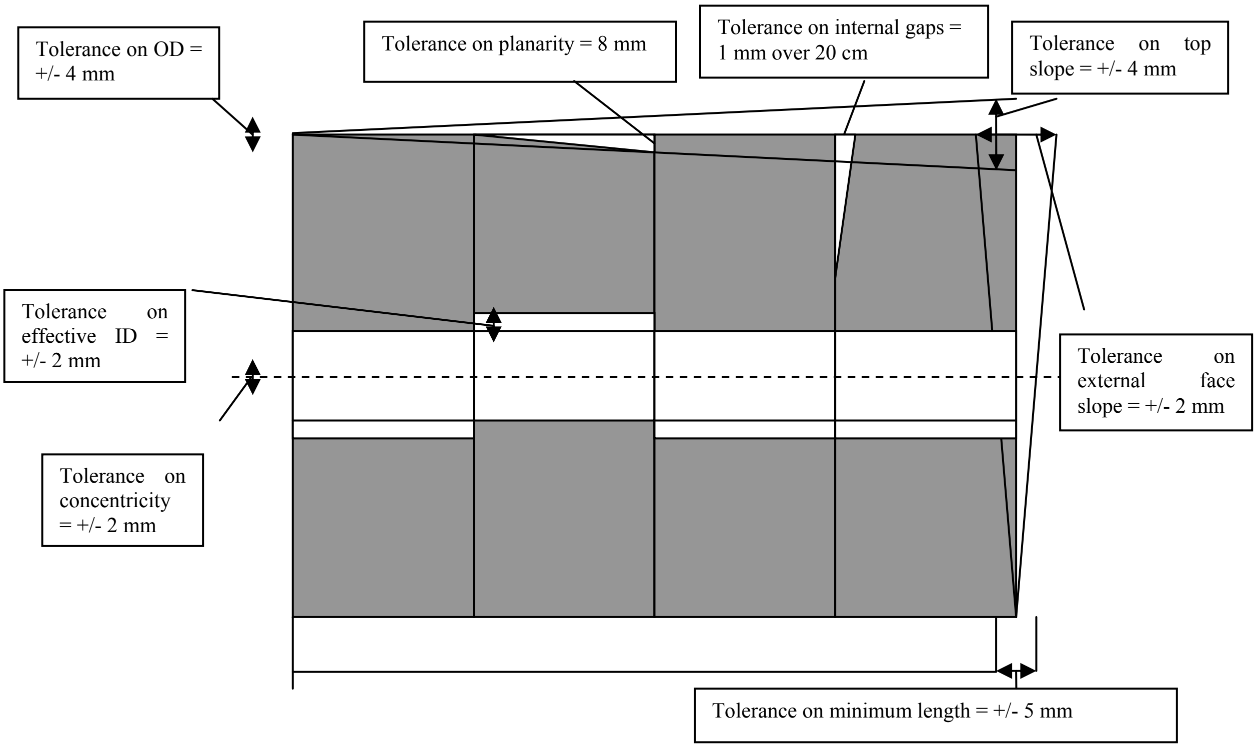


Figure 4: Tolerances for individual rings and for ring assemblies

1.2.3 Summary of technical evolution

The work programme was developed systematically as per the order listed in the objectives below:

a) The geometrical dimensions with the associated tolerances (as posted above in the list of objectives) were confirmed as relevant from the very beginning : on the one hand the selected Module 3 contractor (i.e. for demonstration of heavy load transportation by means of air cushion technology) accepted those values as compatible (in terms of mechanical clearances) with its own technical assignments, while on the other hand the 2 competitors contacted for the fabrication of the cold compacted rings indicated that those dimensions were also compatible with their own assessment of compacted rings/discs fabrication tolerances;

b) Following the selection of a contractor (a consortium of companies called GME), the buffer material used, a bentonite/ quartz sand mixture (70/30), was characterized in a laboratory (including bench scale testing of different samples with variable water content and different compaction pressure values) in order to optimize the fabrication process and to check the compatibility amongst other performances of the cold compacted material with the required swelling pressure and conductivity;
c) The necessary pressing force was determined (a compacting pressure of 80 MPa implied a pressing force exerted around 45 000 / 50 000 tonnes) and the relevant press selected (the only suitable press available in Europe turned out to be the Aubert & Duval press at Issoire in France- see **Figure 13**);
d) The mould (for production of the rings and discs), was designed to cope with the required pressure and to suit the geometrical dimensions and functional limitations of the selected press. The fabrication of the various pieces of the mould involved some very demanding casting and machining. **Figure 14** shows the mould during dry assembly test;
e) The fabrication of 10 rings/2 discs took place in 3pressing campaigns between June and December 2006;
f) The equipment for assembly, packaging and transportation of the rings in sets of 4 was designed, fabricated and tested;
g) Some extra-work was finally added to the initial programme: additional testing related to lifting a ring by means of a mandrill inserted through the central hole and a destructive shear strength test ("Brazilian test") were also successfully executed.

1.2.4 Results

The work turned out to be totally successful and well in line with the posted objectives:

a. The buffer mixture characteristics obtained were in line with the requirements,
b. The rings and discs produced complied thoroughly with the geometrical requirements and had a smooth surface (**Figure 15** shows a ring just after stripping from the mould while **Figure 16** shows a detail of the upper side of a ring, displaying a sharp edge and smooth surface as a visible feature of the good geometrical quality of the end product),
c. Samples taken from one of several extra rings fabricated during the two first campaigns confirmed the homogeneity of the compacted material,
d. Lifting of a ring or disc from a horizontal position to a vertical one was carried out with a suction cup device (**Figure 17**) in conjunction with a tilting frame,
e. The final lifting and transportation (inside a special container) was assured by a special yoke (**Figure 18)**
f. The capacity of lifting individually each disc through its central hole with a simple mandrel was also evidenced (**Figure 19**),
g. Finally the shearing strength evaluated at the end of the Brazilian test was 80 % of that obtained on samples in previous laboratory measurements, thus evidencing that virtually no scale effect was to be taken into consideration, even with a mono-axial pressing force (**Figure 20**).

1.3 Backfilling of a horizontal annular gap (by ONDRAF/NIRAS)

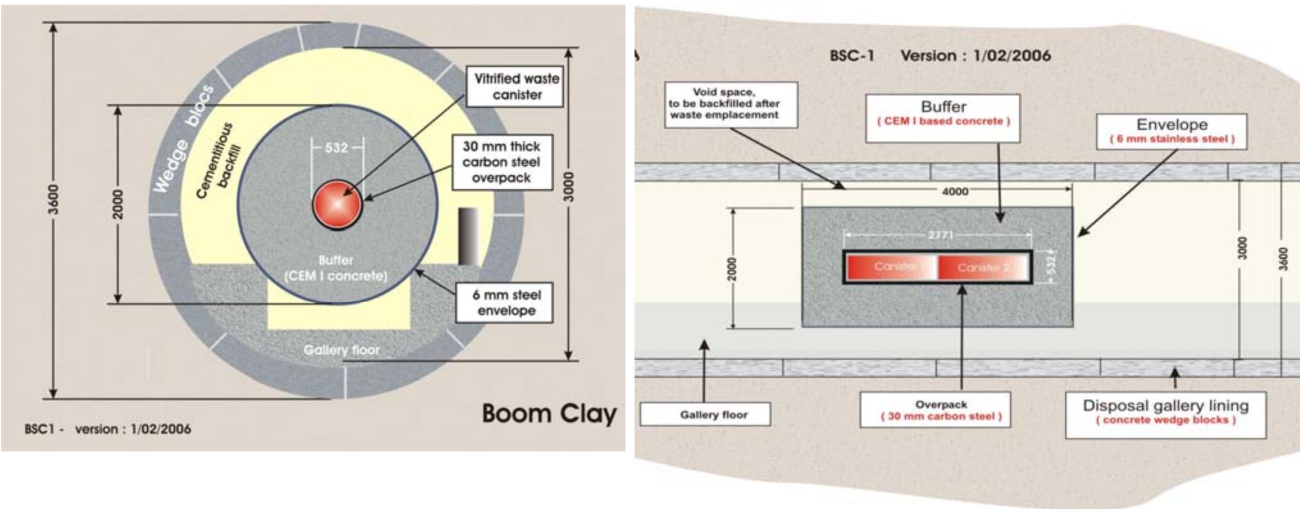
1.3.1 Background

In 2003, resulting from the redesign process after the NEA Peer Review [1], O/N adopted the horizontal Supercontainer as its reference concept for the disposal of HLW. In the Supercontainer concept, the waste canisters are placed within a carbon steel overpack, which is surrounded by a high pH concrete buffer (see **Figure 5**). A high pH material was chosen for the buffer with the aim to create a corrosion-protective environment for the overpack [2].

In this disposal concept for HLW, the primary function of the backfill component is to prevent cave in of the disposal drift, which might damage the Supercontainer or distort the host rock surrounding the drift. The requirements for the backfill are further determined by a number of constraints, relating to long-term safety as well as to operational feasibility and performance capacity.

Because of its straightforward chemical compatibility with the disposal concept and the perceived better opportunities for achieving the industrial performance, the grout injection technique is considered by O/N to be the reference solution for backfilling disposal galleries.

Nevertheless, alternative backfill solutions are still being considered by O/N. These solutions are based on a projection, by use of a dry-gun technique, of a dry granular material into the annular gap between the Supercontainer and the disposal gallery lining.



(a) (b)

Figure 5: Schematic representation of Supercontainer concept - radial (a) and axial (b) cross-section

1.3.2 Objectives

The general objective of the work was to test the backfilling of the annular void in the disposal concept for HLW with both types of solution (grout injection and dry-gun projection).

More specific objectives:

- Grout backfilling: to test, first on a 2/3rd scale mockup and then on a 30 m long full scale mockup, whether the annular gap can be filled within a time frame during which the fluidity of the grout can normally be guaranteed (i.e. about 5 hours) and to achieve a quasi complete filling of the void with homogeneous backfill material. The composition of the specific grout is predominantly determined by long-term phenomenological requirements.
- Dry granular materials: to test on a 2/3rd scale mockup whether the annular gap can be filled, using the dry-gun technique, at a linear pace that would allow application in the actual repository (i.e. faster than 1 m/h) and to achieve a quasi complete filling of the void with homogeneous backfill material. The work involved a pre-selection of the most promising dry granular materials, while focusing on the technological aspects. Robust projection equipment was designed specifically for operating under the mechanically harsh conditions invoked in the annular gap environment by the dry-gun technique.

1.3.3 Summary of technical evolution of the work

The work passed through the following sequence: (1) definition of requirements and gathering of input data, (2) selection/composition of backfill materials, (3) design and construction of reduced-scale mockups (3) execution of backfill tests on reduced-scale mockups, (4) full-scale mockup testing.

The definition of requirements and gathering of input data was part of Work Package 1. The selection/composition of backfill materials and the design and construction of reduced-scale mockups was part of Work Package 2. The reduced-scale mockup testing was part of Work Package 3. The full-scale mockup testing was part of Work Package 4.1.

1.3.4 Results

Backfill materials

The development of a specific grout fulfilling the requirements was a key process that was sub-contracted to BASF Construction Chemical Belgium. It resulted in a dry premix, composed of clinker cement, calcium carbonate powder, fine sand and a limited addition of a polycarboxylate ether-based superplasticizer. To obtain the desired grout only water, according to a pre-determined water/cement ratio, needed to be added

A materials survey, accompanied by pre-testing using the dry-gun projection technique in August 2005, rendered the following list of granular material for possible use as backfill: pure sand (SiO_2), pure bentonite (MX-80), sand-bentonite mixture (25/75), sand-cement mixture (90/10), and bentonite-cement mixture (85/15). The range of materials is schematically represented by **Figure 6**.

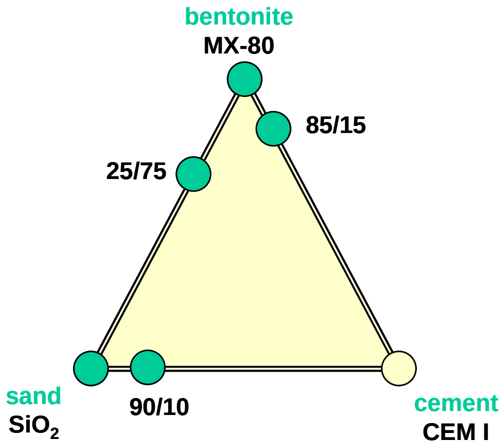


Figure 6: Schematic representation of range of used dry granular backfill materials

Grout injection

After reduced-scale and full-scale testing, it can be concluded that the feasibility of the grout injection technique was successfully demonstrated. However, the full-scale test indicated that the water-over-cement factor (W/C) of the grout will need to be adjusted (lowered) in future development work, because the specific backfill grout failed to become hard after injection.

Dry materials projection

The reduced-scale tests successfully demonstrated the feasibility of the use of the dry-gun technique to backfill the annular gap. It should however be noted that the work did not address the issue of chemical compatibility with the Supercontainer concept.

Logistical needs

The testing focused on the process of backfilling the annular gap. The tests were performed on the surface and not underground in-situ. The tests did not specifically address the upstream logistical aspects. Nevertheless, the tests did stir the awareness of the need to devote specific future development work to the study of the logistical needs behind the backfill operations.

1.4 Granular buffer in combination with prefabricated blocks (by NAGRA)

1.4.1 Background

NAGRA's reference concept for radioactive waste disposal is based on several fundamental requirements and basic ideas. The most fundamental (high-level) requirements for a repository are the multi-barrier system with built-in redundant barriers and the principle of robustness. Therefore, the proposed repository consists of a system of engineered and natural barriers designed to provide safety through isolation of the wastes in a stable geological environment. The depth of the planned repository is 400 – 900 m below surface in the case of the over consolidated claystone (Opalinus Clay). The repository is required to provide a set of engineered barriers that act in a complementary manner with the natural geological barrier to contribute to the safety functions of "confinement" and "attenuation". The principles of predictability, avoidance of detrimental phenomena and insensitivity to detrimental phenomena apply to the engineered barriers as well as to the geological setting.

The design of the repository has been outlined in the different technical reports "Project Opalinus Clay" [3][4][5], which have been submitted to the authorities. A detailed international Peer Review [6] of NAGRA's post-closure radiological safety assessment of the disposal concept in Opalinus Clay of the Zürcher Weinland attested that "the waste emplacement strategy and the use of multiple seals to compartmentalize and isolate the waste packages are feasible and prudent".

Based on technological (ease of remote handling) and geotechnical constraints (non-cylindrical shape of tunnels due to potential local instabilities), a buffer system has been designed consisting of the combined use of bentonite blocks as support for the waste canisters and highly-compacted granular bentonite material (see the report by Naundorf & Wollenberg [7]). **Figure 7** shows a cross-section of the conceptual disposal tunnel.

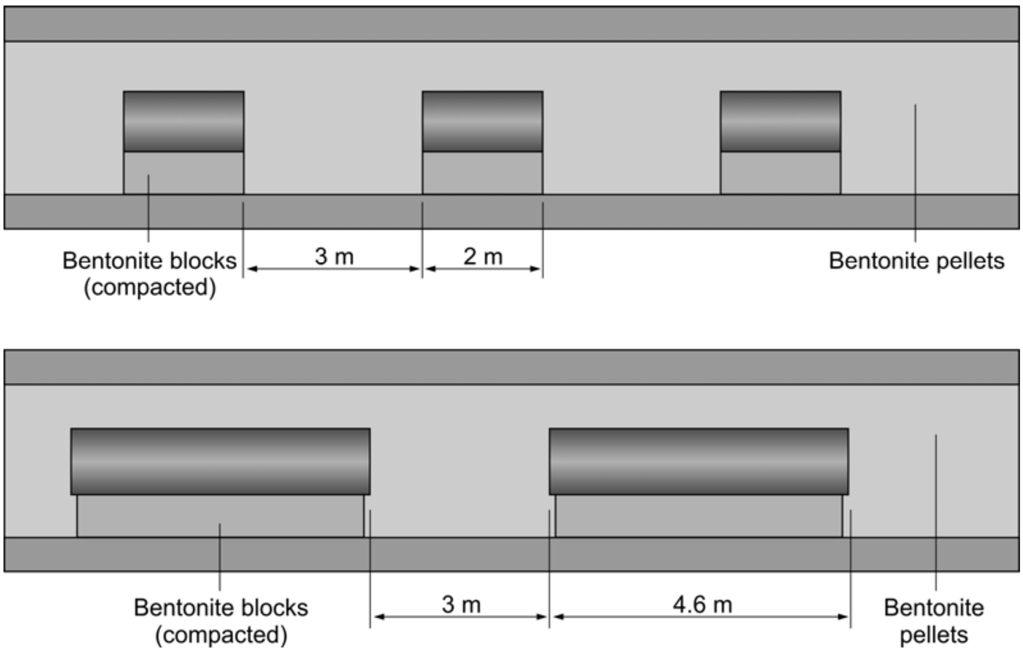


Figure 7: Longitudinal section through emplacement tunnels for SF and vitrified HLW

1.4.2 Objectives

The objectives of NAGRA's work within ESDRED are as follows:

- Testing and demonstrating suitable granular buffer installation techniques on a full scale in surface facilities;
- Verification if the requirements can be fulfilled;
- Optimization of different parameters, if necessary.

The general objectives and the know-how from previous experiments lead to an ambitious project specific target value as follows. The envisaged dry density of the optimized emplaced granular bentonite mixture should be close to 1500 kg/m^3. In the EB test section of Mont Terri Rock Laboratory an overall dry density of 1360 kg/m^3 has been obtained, as reported by Mayor et al [8].

1.4.3 Summary of technical evolution of the work

The first basic tests to demonstrate the feasibility of the proposed design of the combined use of bentonite blocks and granular material were performed within the EB "Engineered Barrier" project at Mont Terri (see the report by Mayor et al [8]), which was co-funded by the EC within the 5th EURATOM Framework Programme (1998-2002). The results clearly outlined the potential of the proposed method leading to the decision to further evaluate potential advancements of the concept and optimizations of the proposed technology.

For the ESDRED Project three types of equipment were evaluated for the emplacement of granular bentonite, namely conveyer, pneumatic and auger method. Based on equipment evaluation trials the auger technique had been identified as preferred method. As first optimization it was decided to develop a twin auger system, instead of the previously used single auger system. For this task the company "Rowa Tunneling Logistics AG", Wangen, Switzerland was contracted to plan, construct and test such a new auger emplacement system.

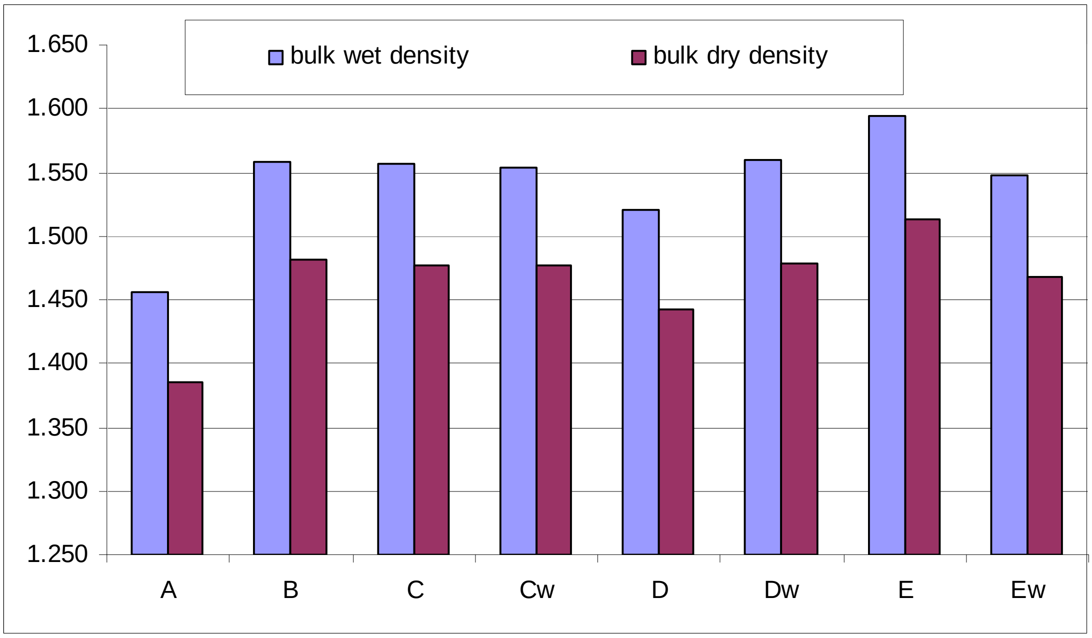
In the previous EB project, a wooden model representing only the upper part of the tunnel situation was used for the emplacement experiments. For the ESDRED project we wanted to have a more realistic and more robust steel model with a round shape representing the full tunnel situation. But for easier handling and for performing more tests in the given time we reduced the scale of the model by 20% (1:1.25). A second improvement with the steel model was the possibility to have 11 openings around the surface of the model for sampling and analyzing the geotechnical bentonite parameters as water content, grain size distribution and emplacement density.

The steel model was backfilled with granular bentonite material using the Twin auger system. The accurate volume of the steel model has been determined by the company Flotron AG (Engineers for Surveying, Photogrammetry and Civil Engineering). This number is quite important for the calculation of the final emplacement density.

1.4.4 Results

The results obtained are very promising that the required densities of the granular buffer material can be reached reliably, as reported by NAGRA in 2007 [8].

Figure 8 provides a summary of the results with the different mixtures (coarse: about 10mm grain size and fine: about 1mm grain size).



A	100 % coarse rounded granular material, embedded in two layers
B	92 % coarse, 8 % fine, two layers
C	85 % coarse, 15 % fine, two layers
Cw	85 % coarse, 15 % fine, two layers
D	70 % coarse, 30 % fine, two layers
Dw	70 % coarse, 30 % fine, repeat run, two layers
E	64 % coarse, 28 % fine, 8 % briquettes, two layers
Ew	64 % coarse, 28 % fine, 8 % briquettes, repeat run, only one layer

Figure 8: Results of the emplacement tests: reached total bulk (wet) density and dry density with different bentonite granulate fraction

1.5 Seal performance testing (by GRS)

1.5.1 Background

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/clay stone 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 optimized 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 Spent Fuel (SF) or vitrified high-level waste (HLW), as illustrated in **Figure 9**. 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 in-house at the GRS laboratory in Braunschweig and in-situ at the Mont Terri Rock Laboratory (MTRL) in Switzerland.

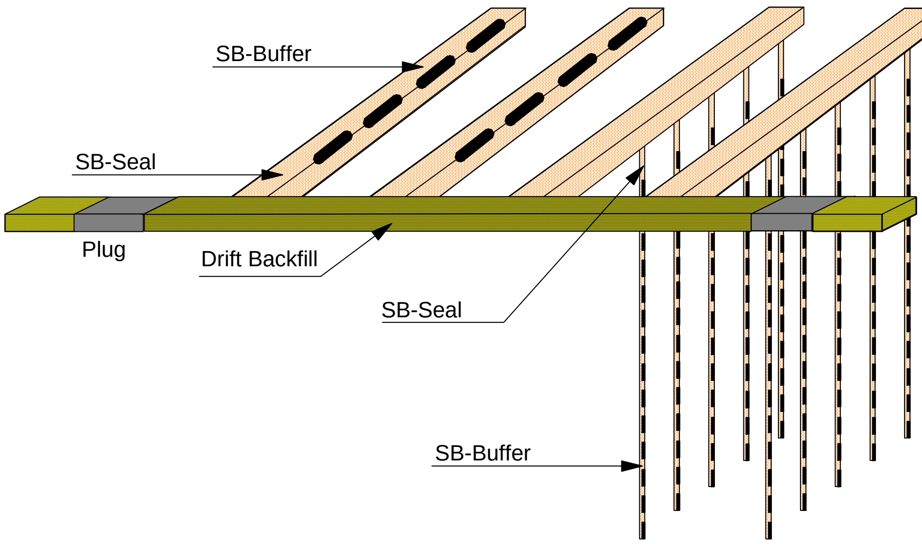


Figure 9: SB-buffer and seal in HLW disposal drifts and boreholes

1.5.2 Objectives

The overall objective of the SB experiment is to test and demonstrate that the sealing properties of clay/sand mixtures determined in the GRS laboratory can technically be realized and maintained under repository relevant in-situ Mont Terri conditions.

The most important material properties that need to be met in a repository and which are to be determined and optimized in the SB experiments are listed in the following:

Permeability to gas

The seal material 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 1E-13 and 1E-15 m^2. According to lab investigations, it remains above 1E-17 m^2 after gas break-through in the saturated state.

Permeability to water

The seal material 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 1E-17 and 1E-18 m^2 is considered sufficient in analogy to the permeability of 1E-14 and 1E-16 m^2 of the excavation disturbed zone (EDZ) in the host rock (Bossart et al., 2002 [9]). 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 entry/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 the NAGRA Technical Report 02-06 [11], 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 Thury et al. (1999), 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 pore water 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 is looked after 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 (Pellegrini et al., 1999 [12]). 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 (Rodwell et al., 1999 [13]). 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.

1.5.3 Summary of technical evolution of the work

The sealing properties of clay/sand mixtures have been preliminarily investigated in detail in the geotechnical laboratory of GRS within two preceding projects, the "Two-Phase Flow" Project (Jockwer et al., 2000 [14]) and the KENTON project (Miehe et al., 2003 [15]). Seal properties such as permeability to water and gas, gas entry and breakthrough pressure, and swelling pressure have been determined for different mixing ratios and different degrees of compaction. Adequate seal properties have been obtained by proper adjustment of the clay/sand ratio.

The investigations of the 2-Phase Flow and the KENTON projects have shown that the single-phase permeability to gas was not significant 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 2.3E-13 – 1.2E-12 m^2. In contrast to that, the clay content clearly affected the single-phase permeability to water.

The water permeability was measured at 2.9E-13 – 5.3E-13 m^2 (10 % clay), 1.2E-16 – 5.3E-15 m^2 (25 % clay), and < 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 correspondent gas break-through pressure was measured to 0.05 MPa.

Because the results of both projects were quite promising it was concluded to demonstrate and qualify the advantageous sealing properties of clay/sand-sealing materials under repository representative in-situ conditions at the MTRL.

Hence, in summer 2003, GRS started the SB (**S**elf-sealing Clay/Sand-**B**arriers) project which is performed under consideration of the following three major project phases:

1. Laboratory investigations for final selection of suited material mixtures and development of installation/emplacement techniques;
2. Large-scale laboratory mockup testing for the development of suited material installation techniques and testing of measuring instrumentation;
3. In-situ testing in boreholes under representative in-situ conditions in the Mont Terri Rock Laboratory.

1.5.4 Results

GRS Laboratory

On basis of experiences obtained in the KENTON-project, the laboratory investigations for the selection of optimized material mixtures within the SB experiment were performed on mixtures with clay contents of 35%, 50% and 70%.

The seal material under investigation consists of bentonite powder (Calcigel) and ordinary sand. The grain density of the sand was 2.65 g/cm^3, and the grain density of the Calcigel was 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 entry/break-through pressure, and the gas permeability after break-through.

Table 1 summarizes the ranges and the mean values (in parentheses) of the determined properties for the investigated clay/sand mixtures and compares them to the requirements described in Section 1.5.2. It is obvious that the 35clay/65sand and 50clay/50sand mixtures meet the requirements completely. 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. From these results, the clay/sand mixtures with the ratios of 35/65 and 50/50 have been selected for further mockup and in-situ testing.

Table 1: Comparison of the measured parameters to the 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

Mockup testing

The mockup tests were started in October 2004. The investigations of mockup N°1 were performed with the most promising 35/65 clay/sand mixture. The installation density of the seal amounted to 1.78 g/cm^3. The test was started by determining the gas permeability, which was determined to 6.5E-14 m^2. 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 (compare Table 1).

Based on the experiences from this test, the mockup N°2 was prepared more carefully. The installation density of the seal element amounted here to 1.94 g/cm^3, which is very close to the target value. The initial gas permeability was determined to 6.2E-14 m^2 which corresponds also very well with the gas permeability determined in the preceding investigations on small samples (see Table 1). Seal saturation in the mockup N°2 was started in April 2005 at an injection pressure of 1.1 MPa.

The first water break-through, indicating a situation close to full seal saturation in some parts of the seal, was observed in September 2007, after about 29 months of testing. The water injection was stopped by reducing the injection pressure to zero on July 6, 2008 after full saturation was reached. At this stage the water inflow and outflow rates had equalized at about 10 ml/day yielding a water permeability value of about 3E-18 m^2, which is in very good agreement with the data determined from the small samples previously tested in the laboratory. The swelling pressure was then allowed to stabilize in the entire seal before the pending gas injection test was started on 7 January 2009. Both, the water permeability value, as well as the gas entry pressure of 3.5 bars determined in the early stage of the gas injection test, excellently confirm the expected optimized sealing properties of the 35/65 clay sand mixture. Full seal saturation, however, was only reached in July 2008 after about 38 months which significantly exceeds the predicted saturation time by about a factor of 7. Further research is needed to clarify this discrepancy in relation to the predicted 170 day saturation period, i.e. to enhance the understanding of the process in order to further improve the model.

In-situ testing

The in-situ experiments are designed in principle the same way as the mockup experiments. However, because of the long saturation times experienced in the mockup tests the seal length was reduced from 1 m to 0.5 m in the case of the experiments using the 50/50 clay/sand seal and the 100/0 pure bentonite seal.

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. So far, no water has been collected at the upper outlet which indicates ongoing saturation of the seal. On basis of the experiences from the mockup tests the water break-through at the seal in borehole BSB2 test is expected to occur now within a reasonable period of time in 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 put 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 24 bars. 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. 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.

As mentioned above the first water break-through and seal saturation in the in-situ experiments is expected to occur within a reasonable period of time in 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 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.

The results of the SB-experiments obtained so far in the mockup at GRS' laboratory in Braunschweig as well as *in-situ* at the Mont Terri Underground Laboratory 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 mockup 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.

1.6 Seal material installation in annular configuration (by EURIDICE)

1.6.1 Background

The installation of the hydraulic seal fits in the framework of the in-situ experiment by EURIDICE to investigate the impact of the thermal load of heat-generating waste on the Boom Clay host rock. To this purpose a 45 m long PRACLAY gallery was constructed in 2007 in HADES (the underground research facility in Mol). This gallery will be subjected to a 10-year long thermal experiment. An axial cross-section of the PRACLAY gallery, displaying the principal components of the PRACLAY gallery and main components of the in-situ experiment is shown in **Figure 10**.

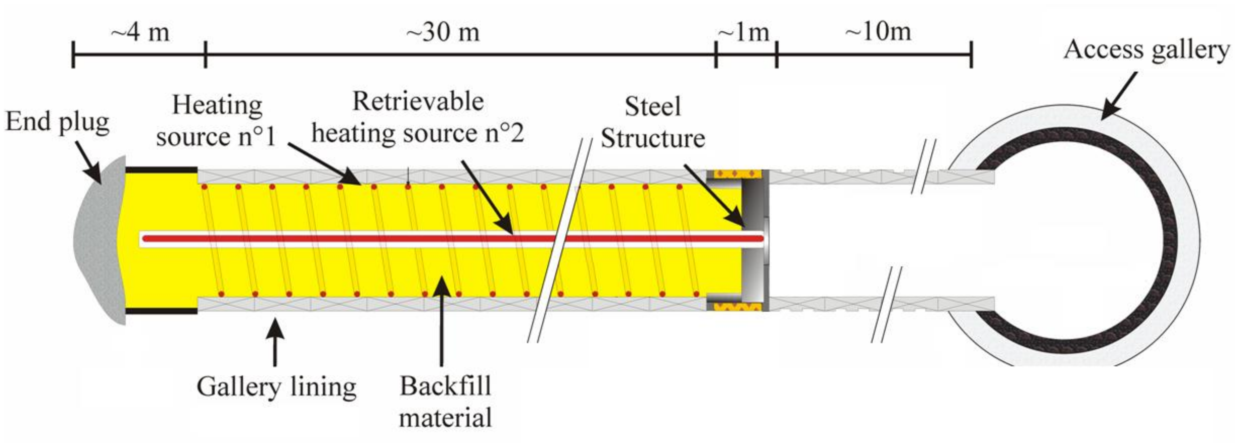


Figure 10: PRACLAY gallery and main components of the In-Situ experiment

As it is not possible to realize the experiment at the time scale of a disposal system, it was decided to carry out the PRACLAY experiment under the most critical conditions in terms of THM responses of the Boom Clay. An important issue is the pressure build up as a result of the heating. Among others, it needs to be verified that an excess pore pressure could not lead to the liquefaction of Boom Clay as a consequence of the decrease in effective stress. Numerical scoping calculations showed that the thermal induced pore pressure build up is much more pronounced in undrained conditions (impermeable boundary) than in drained condition (permeable boundary). The undrained conditions therefore correspond to the most critical conditions

For the PRACLAY in-situ experiment, this undrained condition (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.

1.6.2 Objectives

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.

1.6.3 Summary of technical evolution of the work

The work on the PRACLAY seal installation test has been performed as part of Work Package 4. A first summary of functional requirements for the seal material was completed as part of Work Package 2.

The design of the seal support structure as the analyses on the seal material were largely performed in parallel. The work on the seal material started in 2006, when through literature study and a number of scoping analyses MX-80 was selected. Laboratory testing and scoping calculations were executed in 2007 and 2008. The PRACLAY gallery was constructed in October and November 2007. The seal support structure had to be redesigned. This work, and the actual implementation of the seal installation, was contracted according to a public tender procedure in 2008. The redesign was the main reason for the delay that was suffered within the project.

Presently, the design of the PRACLAY seal is complete, but the actual in-situ installation of the seal in the PRACLAY gallery remains to be done. It will fall beyond the contractual end date of ESDRED. The installation is now foreseen for mid-2009. The delivery of the materials and the in-workshop construction of the seal will take about 7 months, starting from 20 October 2008. Then the feasibility to install the seal in the gallery will be demonstrated by a pre-assembly on surface. Following the surface pre-assembly checks, the seal will be transported to the site for its underground installation. The underground installation is estimated to take about 2 months.

1.6.4 Results

With respect to the objectives within ESDRED, 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 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 mid-2009.

1.7 Micro-seismic non-intrusive monitoring development (by NDA)

1.7.1 Background

Repository monitoring is a fundamental component of national disposal programmes, and is an important constituent of the ESDRED project. Monitoring has a role to play through all phases of repository development, from the establishment of baseline conditions, through construction and operation of a repository (to ensure operational safety), through to closure and post-closure. Parameters such as temperature, groundwater inflow, humidity and radioactivity might be monitored.

A key principle identified by the European Union Thematic Network Study [16] on the role of monitoring states that, "*monitoring must be implemented in such a way as not to be detrimental to long term safety*". The development of effective non-intrusive techniques for repository monitoring would provide methods for monitoring without affecting the passive safety of intact repository barriers. Non-intrusive, remote monitoring also avoids problems associated with the failure of monitoring sensors located within the EBS, which can only be repaired or replaced by disturbing the near-field of the repository system.

A programme of monitoring will be undertaken throughout the phases of repository development and could employ a number of techniques which are intrusive to varying degrees. For example, conventional, direct monitoring might incorporate sensors emplaced within the repository excavations (and perhaps within the EBS). The output from these sensors would be transmitted through wires to observation points. Whilst such approaches are commonplace in a variety of industrial applications and would be applicable during the construction and operation phases of the repository, both data collection and data transmission activities would have the potential to compromise the passive safety of the repository and the EBS, and therefore, would not be applied post-emplacement.

A less intrusive approach would employ wireless data transmission, sometimes referred to as through-the-earth, (TTE) transmission. This approach might make use of conventional or novel monitoring sensors, but, importantly, the integrity of engineered and natural repository barriers is maintained by transmitting the data remotely using, for example, radio frequency signals. Research in this area is ongoing by a number of waste management organisations. Key challenges include the reliability and lifetime of wireless data transmitters, particularly their power supply. These factors, which include the continued integrity and reliability of the monitoring sensors, the data transmitters, sustaining the power supply for wireless transmission of data and the ability to transmit data through many hundreds of metres of solid rock, may limit the scope of monitoring by this method.

With non-intrusive techniques the sensors would be located outside of the engineered barrier system and hence overcome the potential degradation in EBS performance that would result from conventional wired systems. Non-intrusive techniques also avoid the problems associated with the failure of monitoring sensors, which for conventional (intrusive) or wireless monitoring could only be renewed or replaced by disturbing the EBS.

Different non-intrusive techniques are suitable for monitoring the near-field, depending on the scale of the process to be monitored. Non-intrusive techniques carried out at the surface typically facilitate monitoring of large-scale, regional processes. Sub-surface non-intrusive monitoring tends to focus on smaller, repository scale processes, using techniques such as seismic tomography. A number of geophysical techniques for non-intrusive monitoring of a repository were identified by Module 1 partners as candidates for further study; these included:

- Electrical Resistivity/Impedance Imaging (ERI)
- Seismic Tomography

- Micro-seismic (MS) and Acoustic Emission (AE) Monitoring
- Seismic Reflection
- Ground Penetrating Radar (GPR)

The ESDRED Module 1 partners met in early 2005 to consider repository concepts, monitoring objectives and potential non-intrusive techniques. The resolution of ERI was considered to be too low and so this option was rejected from further consideration. In addition, the risk of anomalous, erroneous or noisy data arising from short circuits of the applied current through metallic components of the EBS was considered to be high for most of the Module 1 partners' repository concepts. MS/AE techniques were considered feasible within the scope of the ESDRED programme. However, monitoring of changes in temperature, water saturation, gas and fluid migration and/or stress would only possible using this technique if changes in these properties resulted in brittle failure events. This could limit the extent of data collection, particularly within the relatively short time frame of the project. Cross-hole seismic tomography was therefore selected as the favoured non-intrusive monitoring technique for obtaining useful and reliable information for the various conceptual repository designs and addressing the range of monitoring requirements expressed by Module 1 partners. **Figure 11** provides a schematic representation of this technique.

It was also decided by the Module 1 partners to take the opportunity offered by an already planned experiment at Mont Terri to use this as the location for setting up the non-intrusive monitoring experiments configuration.

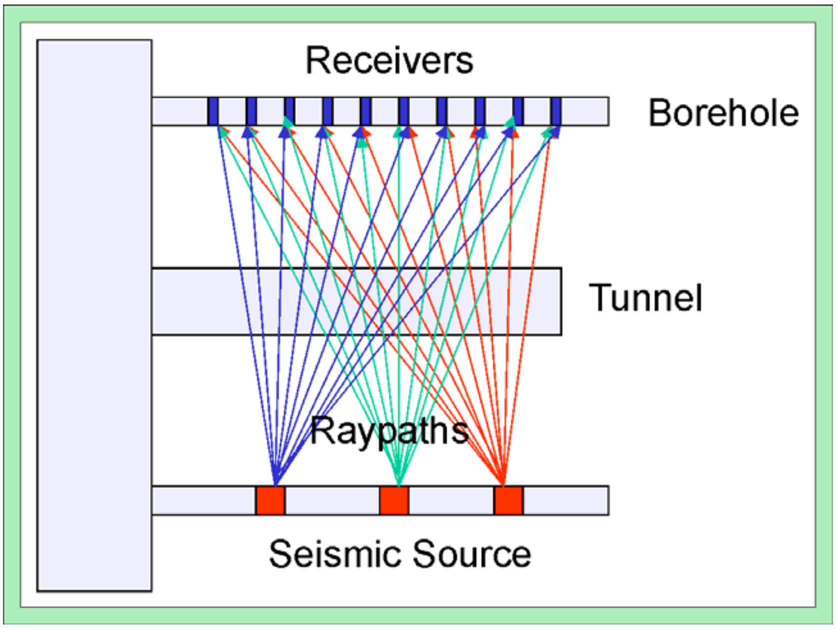


Figure 11: Schematic representation of cross-hole seismic tomography

1.7.2 Objectives

Having decided on a seismic tomography development program based on an experimental setup at the location of the already existing HG-A experiment at Mont Terri URL, the principal objectives of the work were defined as follows (NDA, 2006 [17]):

- To further evaluate and develop cross-hole seismic tomography techniques for non-intrusive monitoring of repository systems, by investigating the potential of the technique to monitor the performance of the EBS and the near-field host rock at Mont Terri;
- To provide recommendations for designing repository monitoring programmes incorporating non-intrusive techniques

1.7.3 Summary of technical evolution of the work

The non-intrusive monitoring development work within ESDRED constituted an entire separate work package, i.e. Work Package 5. In sequential order, the technical work consisted of:

- taking a justified decision on the type of technology to develop further for non-intrusive monitoring purposes and a location for an experimental set-up;
- design, procurement of parts and equipment and installation of the experimental set-up;
- execution of a number of measurement campaigns, with hold-points for evaluation and possible adjustment of the experimental set-up. The measurement campaigns were to be scheduled according to the key phases in the HG-A experiment (empty micro-tunnel, sand backfilling, water-saturation of backfill, nitrogen gas injection);
- in parallel, based on information from the measurements, the establishment of computer models to:
    1. simulate the anisotropic behavior of the host rock, for a better understanding of the effects caused by the anisotropy
    2. perform full waveform inversion, for drawing a more complete image from the seismic echoes.

The technical components of the activities, including field measurement, research and full waveform inversion of tomographic data have been undertaken by the Swiss Federal Institute of Technology, Zurich (ETH), in the framework of a 4-year PhD thesis sponsored by the NDA and undertaken by Edgar Manukyan under the supervision of Dr. Hansruedi Maurer and Professor Alan Green at ETH.

1.7.4 Results

Six measurement campaigns have so far been performed during the period March 2006 to June 2008. Measurement campaigns prior to and after gas injection are currently planned for mid-2009, outside of ESDRED.

For the interpretation of the measured data, a computer model of the anisotropic host rock environment of the HG-A tunnel was developed and a full waveform inversion code is in the process of being developed.

The results of seismic investigations on the HG-A experiment at Mont Terri suggest that cross-hole travel-times do not enable information to be gathered about the state of a 1 m diameter micro-tunnel that lies midway between source and receiver boreholes separated by distances of 5-30 m. In contrast, data recorded on geophones mounted within the micro-tunnel provide diagnostic information about the micro-tunnel fill and the state of the micro-tunnel EDZ. Changes in the micro-tunnel fill and EDZ result in marked variations in seismic wave arrival times, polarities and waveforms.

2 PROGRAM IMPLEMENTATION

2.1 Cold compaction of bentonite buffer rings (by ANDRA)

2.1.1 Logic of project implementation and planning

As also described in Section 1.2.3, the work programme followed a very logical planning: the first task was to define clearly and summarize the Input data and functional requirements. The results of this task are summarized in Sections 2.1.2, 1.2.1 and 1.2.2. The following task consisted of selecting a Contractor in charge of designing and fabricating the mixture, the mould and the rings, associated with the relevant handling and packaging equipment. The next steps (sub-contracted to the selected Contractor, called GME and closely followed-up by ANDRA throughout the implementation of its contract) consisted in characterizing the sand/bentonite mixture, apprehend the necessary compacting pressure, design and fabricate a mould (compatible with the press selected for the cold compaction), proceed with the production of the rings and discs as per the geometrical dimensions set, design/fabricate/test the handling/packaging items, evaluate at the end the full process. This planning was effectively and successfully implemented between late 2003 and early 2007.

2.1.2 Input data and functional requirements

The general background of ANDRA's research is summarized in Section 1.2.1, as well as in Section 1.2.2.

Table 2 below focuses on the functions to be fulfilled by the buffer mixture (the engineered barrier) as per the phenomenology considered in ANDRA's repository concept.

Table 2: Functional requirements of buffer material in ANDRA HLW disposal concept

FUNCTIONAL REQUIREMENTS OF BUFFER MATERIAL IN ANDRA HLW DISPOSAL CONCEPT			
Description of Objective	**Time Frame of Objective**	**Associated Material Parameters and Criteria**	
		FUNCTIONS	
To isolate the canister from the rock and to support and protect it against rock displacements.	**Before** canister loss of integrity, i.e. < a few thousand years	Plasticity	As high as possible (most swelling clays on the market are satisfactory)
To isolate the canister from groundwater flow and transport processes taking place in the surrounding rock; achieved by providing a low-permeability medium for water flow around the waste packages.		Hydraulic conductivity K	$K < 10^{-12}$ m/s
		Swelling pressure P	P > 1 MPa after sliding of the concrete plug P < 7 MPa at any time
To create a geochemical environment that will protect against corrosion		Compatibility with steel (pH)	pH not too low
		Hydraulic conductivity	$K < 10^{-12}$ m/s
To create a geochemical environment that will promote the stability of the matrix glass and U/Pu oxides	**After** canister loss of integrity, i .e. > a few thousand years	Compatibility with glass	
		Hydraulic conductivity	$K < 10^{-12}$ m/s
		Swelling capacity	P > 1 MPa after sliding of the concrete plug P < 7 MPa at any time
To delay radionuclides release by retarding the transport of radionuclides		Hydraulic conductivity	$K < 10^{-12}$ m/s
		Swelling pressure P	P > 1 MPa after sliding of the concrete plug P < 7 MPa at any time
		Sorption	
		CONSTRAINTS	
Buffer should allow gas to escape (as long as steel parts are present)	Many thousands of years	Gas permeability	As high as possible
Buffer should be a good thermal conductor (as compared to rock mass) i.e. should not act as an insulator	Most critical during thermal climax, i.e. a few tens of years. Likely to occur before saturation	Thermal conductivity λ (which depends on dry density, nature of additives, water content)	λ > 1.2 W/m/K (before saturation and swelling- loss of conductivity due to gaps to be added)
	Also important during the remainder of the thermal phase, i.e. from a few centuries to a few thousands of years		λ > 1.5 W/m/K (after saturation and swelling- no more gaps)

2.1.3 Characterization in Laboratory

Permeability and swelling pressure criteria lead to the selection of swelling clay as main component of the buffer. The swelling clay is mixed with sand.

Natural sodium swelling clay is selected in order to satisfy the long term chemical stability. Various Montmorillonite are available on the market. The Wyoming MX-80 has been chosen for convenience (many suppliers in Europe, many studies by SKB / Clay Technology).

Silica sand is selected for chemical compatibility with the swelling clay.

Graphite is rejected as it may accelerate steel corrosion.

The quantity of sand that could be added is defined as follows:

- sand content has an impact on permeability; it is generally considered that sand content must not exceed 40% in order not to deteriorate the permeability characteristics of the buffer.
- sand content and sand granulometry have an impact on compaction conditions and on strength of the mixture, while thermal conductivity of buffer is significantly improved by the admixture of sand.

Based on these considerations, a mixture of **70% clay (MX-80) and 30% sand (quartz)** was selected.

Laboratory tests were performed in order to check whether this choice could fulfil the various required values. At the end results were effectively provided for the following items:

- ***Water content and compaction pressure:*** The tests showed that the optimum compaction conditions are achieved for water contents lower than 10%, while 80 MPa was an optimum compacting pressure value,
- ***Thermal conductivity:*** The results were satisfactory. A buffer mixture with a degree of saturation of 80% (target value in the design) displays a thermal conductivity of approximately 1.5 W/m/°C, which is higher than the threshold value of 1.2 W/m/°C. At saturation, a thermal conductivity of 1.8 W/M/°C is extrapolated, which is again higher than the threshold value of 1.5 W/m/°C. Those values are acceptable.
- ***Strength tests:*** Results indicated that with a compression pressure of 80 MPa, the compressive strength is about 8.5 MPa which is slightly lower than the target value of 10MPa. This value is however not considered as critical. Same for the shear strength, measured at 0.9 MPa instead of 1 MPa as a posted target.
- ***Swelling pressure:*** Considering 15% of annular space to be filled by the swelling mixture in the repository cell, a clay water content of 16.5%, and a compaction pressure of 80 MPa, the swelling pressure measured stayed within the target (1 MPa < P < 7 MPa).
- ***Hydraulic conductivity:*** All the measurements made fulfilled the requirement of 10^{-12} m/s.

2.1.4 Design and computer modeling of mould

The mould dimensions had to take into account the post swelling of buffer rings so that the final dimensions of the rings would meet the geometrical requirements.

The basic geometrical characteristics of the mould to be built were obtained via computer-aided design. They are illustrated in the schematics of **Figure 12** below:

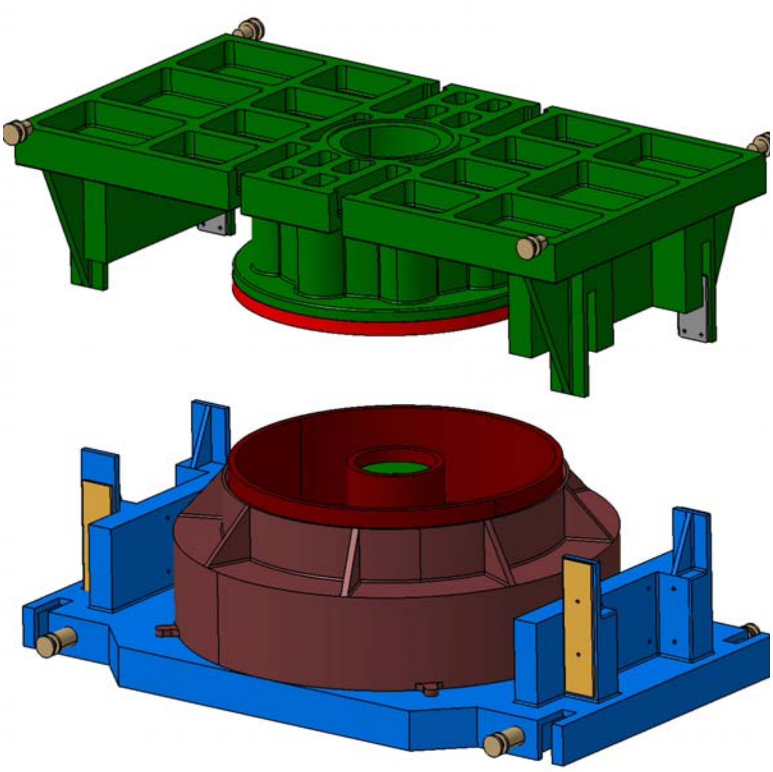


Figure 12: 3D view of the mould as per computer-aided design

2.1.5 Implementation and main achievements

The main results are summarized in Section 1.2.4. They are illustrated below.

The press shown in **Figure 13**, located in Issoire (center of France), owned and operated by AUBERT&DUVAL, is the biggest in Western Europe in terms of pressing force (65 000 tonnes). It was used in 4 shifts of 8 hours during 3 pressing campaigns (in June and December 2006). Amongst the many challenges imposed to the GME for the use of such a press, there was a very demanding schedule constraint: a time window pre-defined by the owner who was giving absolute priority to its daily business and clients (air industry).

The fabrication of the mould was also a challenge of its own, considering the large quantities of melted cast-iron to be poured in one time for the biggest components (over 35 tonnes). The machining and assembling of the mould pieces called for outstanding means found in Montchanin-Le Creusot, with a machining contractor called Le Creusot-Mécanique. The end product is shown in **Figure 14** during dry assembly test.

Figure 13: Press at Issoire

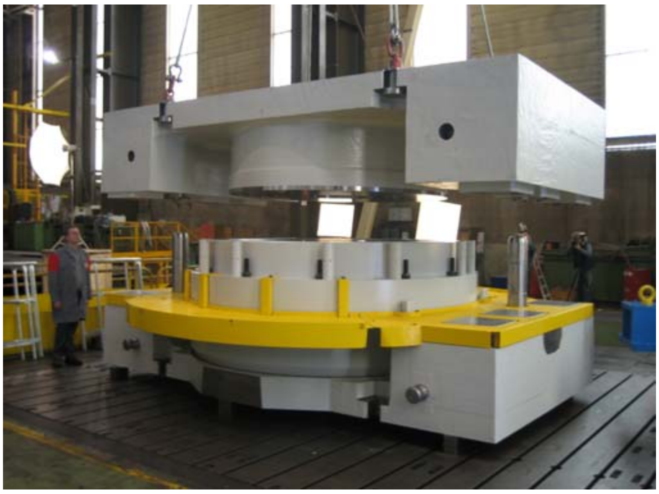


Figure 14: Assembled mould

The production of 10 rings and 2 discs (during the last pressing campaign in December 2006) was efficient (the 2 first attempts in June 2006 enabled a satisfactory trouble shooting and all the corrective actions necessary for modifying the compaction process/ the mould design were under taken).

Figure 15 and **Figure 16** show a ring right after stripping in Issoire and the good quality surface of the product.

Finally, the ring handling and packaging items were also satisfactorily developed (**Figure 17** and **Figure 18**), even though a simpler and more straight forward method could be positively tested on a spare ring (**Figure 19**).

This spare ring was ultimately destroyed in a Brazilian shearing test at full scale (**Figure 20**), which enabled to check that there was virtually no scale effect concerning the shear strength values found: 0.9 MPa on laboratory sample versus 0.8 MPa on full scale ring.

Figure 15: Ring just after stripping from the mould

Figure 16: Detail of the upper side of a ring

Figure 17: Lifting a disc by suction cup handling device

Figure 18: Deposition by lifting yoke of 4 pre-assembled rings on transport container lower part

Figure 19: Lifting of a ring with a mandrill

Figure 20: "Brazilian" shear strength test

2.1.6 Conclusions and lessons learned

At time of writing this final evaluation report, ANDRA has removed the requirement for installing an engineered barrier around C type waste packages. However, should ANDRA dispose of SF packages in a future repository for which the installation of an engineered barrier could be considered, one may say that ANDRA has acquired know-how and a methodology which could be extrapolated to the fabrication of rings/discs of a larger diameter. This know-how is also transposable for the fabrication of large blocks of compacted buffer of a different geometrical shape.

2.2 Backfilling of a horizontal annular gap (by ONDRAF/NIRAS)

2.2.1 Logic of project implementation and planning

See Section 1.3.3.

2.2.2 Input data and functional requirements

In the O/N disposal concept for high level waste, 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.
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.

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:
    - not disturb the corrosion-protective characteristics of the buffer (in Supercontainer);
    - not act as a thermal isolator;
    - not introduce organic materials that can give rise to migration-enhancing complexes;
    - no excessive expansion or shrinkage or chemically attack the disposal drift wall;
2. constraints related to feasibility:
    - exhibit the physical qualities that will allow it to be pumped or projected into the gap;
    - achieve the needed industrial performance of the process;
    - dust generation and water run-back should remain very limited;
    - limit backfill strength, to keep the option of retrievability open as much as possible.

Table 3 summarizes the derived requirements for the backfill component in the O/N disposal concept for HLW.

Table 3: Requirements of the backfill material in the O/N HLW disposal 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 **mechanical stability** of the disposal drift: 1. by **excessive expansion or shrinkage** with respect to the drift wall 2. by **chemical attack**	1 000 years [(1)]	**thermal expansion** $\leq 10.\ 10^{-6}$ linear per °C **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** *criterion: 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** *criterion: 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** *criterion: time between grout injection and removal of casing ≤ 4 days (current operational objective)* In case of granular backfill: **volumetric projection capacity** *criterion: 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)

2.2.3 Studies and computer modeling

Not applicable.

2.2.4 Laboratory testing

See Section 1.3.4 (backfill materials)

2.2.5 Test program definition

See Section 1.3.3

2.2.6 Set-up of the test facility

Reduced scale mockups (common features)

The reduced-scale tests were performed on two different mockups; one for the grout option and one for the granular materials option. Both mockups have a geometrical configuration similar to a section of disposal gallery in which a Supercontainer has been disposed.

The diameters of the mockups are at 2/3rd of the actual dimensions, which makes them "reduced-scale" mockups. This scale reduction was done for the following practical reasons:

- The main structural components of the mockup are standard available in sizes of about 2/3 of the actual disposal gallery dimensions.
- By reducing the size, also the total weight of each mockup is reduced. This has allowed their location in the workshop next to the first shaft of the URL in Mol. Both mockups were constructed in the spring of 2005, on two specifically prefabricated concrete slabs.

Figure 21 shows the main structural composition applicable to both mockups. The gallery lining in the mockup is represented by a set of two 2.33 m long and 2 m internal diameter reinforced concrete pipes. Each of the pipes rests on a concrete support. The Supercontainer is represented by a 1.3 m diameter and 5 m long carbon-steel tube (in red on the figure), resting on a concrete floor with a shape similar to the floor in the HLW disposal gallery design. The angle under which the carbon-steel tube is mechanically supported is the same as for the Supercontainer in the reference disposal design (i.e. 102°).

The dimensions of the floor are fixed in such a way that the minimum space of the gap between the top of the steel tube and the concrete pipes is made as small as practically possible, in order to test the emplacement technique in its most constrained spatial conditions. In the mockup for grout, a minimum gap space of 15 cm was chosen. In the mockup for granular materials, the minimum gap space was 35 cm.

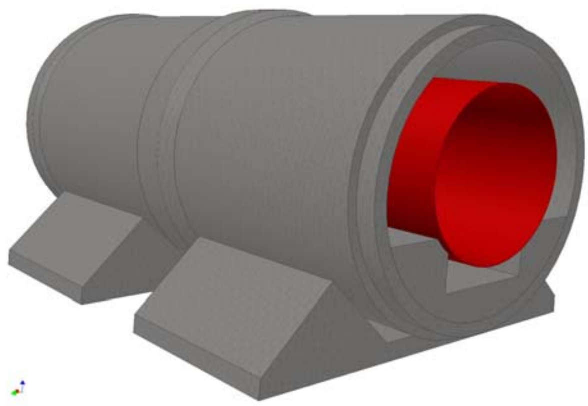


Figure 21: Main structural composition applicable to both reduced-scale mockups

Reduced-scale mockup for grout backfill

The mockup was hermetically closed by two steel lids bolted on the rim of the concrete pipes and hermetically sealed with a chemical anchorage (a resin-like substance). Three injection tubes and one vent nozzle were led through the front lid. The main injection tube (3 inch ID) was installed on the lower face of the concrete floor. It has a length of 3.75 m and thus covers about 2/3 of the mockup length. In the envisaged backfill technique, injection will take place only through this main tube. The other two injection tubes (2.5 inch ID) were installed for backup purposes, incase during the test the injection through the main tube would be unsuccessful. These tubes are about 2.5 m long and thus cover about 1/2 of the mockup length. The vent nozzle (2 inch ID) was mounted on the upper part of the lid, to allow the air to escape as the gap would gradually get filled with grout. To allow the grout to be pumped from the lower part of the void, under the steel tube, into the upper part, three PVC elbow pipes of 10 cm internal diameter were installed on each side of the concrete floor.

A heater was installed inside the steel tube to simulate the heat produced by the HLW. To reflect the thermal inertia of the Supercontainer body, fine dry sand was placed within the steel tube and around the heater. The automatic control is on-off, but the heater can be manually adjusted to certain constant values. The mockup was thermally isolated to limit the time needed to reach the selected temperature and to prevent as much as possible the influence of external temperature variations.

The mockup was instrumented with the following sensors:

- 1 electrical TDR probe and 4 strain gauges, to follow the grout hardening;
- 8 temperature sensors, type Pt-100, to follow the rise of the grout level and the temperature distribution within the backfill;
- 1 thermal conductivity sensor, to follow the evolution of the thermal conductivity of the material.

Furthermore, in order to visualize the rise of the grout during injection, a 2.5 inch ID Plexiglas® pipe was mounted on the front lid and connected to one of the secondary injection tubes.

To ensure the water tightness of the mockup, the void was filled with water and checked for leakages. After the test the water was let down via the main injection tube.

The photograph of **Figure 22**, taken in March 2006 during its construction, provides a good overview of the composition of the mockup.

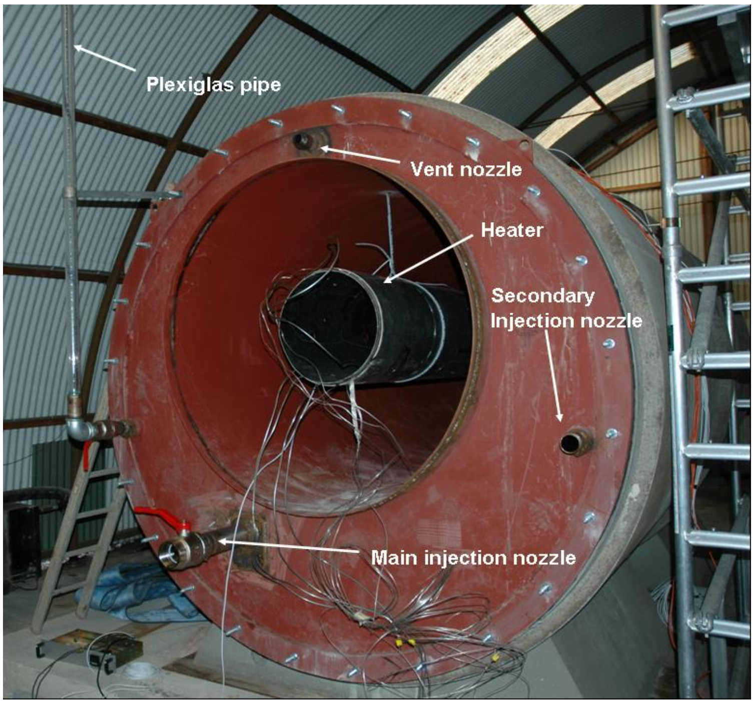


Figure 22: Overview of the mockup for grout (construction status March 2006)

Reduced-scale mockup for granular materials backfill

The main differences of this mockup with the one for grout are the following:

- The mockup is closed by only one, unpenetrated, steel lid.
- To allow the use of the projection vehicle (see further below), the minimum gap thickness was taken to be 35 cm (instead of the 15 cm of the grout mockup). The dimensions of the concrete floor were adapted accordingly;
- Because the heat production by the HLW it is not a critical parameter for the considered granular backfill materials (unlike with the grout), the mockup is not equipped with a heater. Consequently, the inside of the steel tube was not filled with sand either. To prevent deformation of the steel tube under its own weight and that of the backfill, stringer supports were installed inside the tube
- The mockup was not instrumented.

The nozzle for the projection of the granular materials is mounted on a specific vehicle. This projection vehicle is used because it would be impossible, in real-life as well as in the test, to project backfill material through a narrow annular gap over a distance of more than a few meters. It is not possible for a worker to enter the narrow annular space either. The use of some kind of projection vehicle that can move along the length of the gallery is therefore necessary. For the test, a basic projection vehicle system was designed by EURIDICE in collaboration with the SCK•CEN Principal Workshop department.

The projection nozzle is fixed on a steel base plate, which can make a semi-circle movement along an arc-like frame. This radial movement is driven by a combined cable-pulley and chain system, powered by a hydraulic motor. To prevent coning and to achieve a better spreading of the projected material, the nozzle is given an additional nodding movement. This nodding is driven by a piston system, which is also mounted on the base plate. **Figure 23** shows a close-up picture of the projection nozzle during operation. Clearly visible are the base plate on which the nozzle and the piston are mounted, and the cable which pulls the base plate along the arc-like frame. The axial movement of the vehicle occurs on synthetic wheels, sheltered from the harsh conditions inside the gap by a steel frame fixed to the concrete floor. In the system used for the test, the axial movement was hand-driven. The construction of the vehicle and the axial steel frame was undertaken by the by the company BAUDOUIN, located in Mol. **Figure 24** shows the actual setup of the vehicle system in front of the mockup.

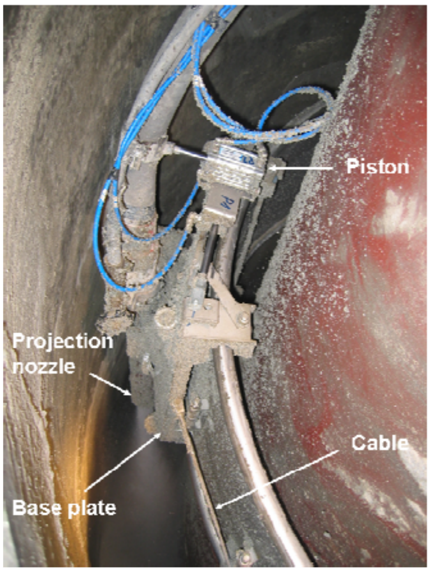


Figure 23: Main structural composition of the reduced-scale mockups

Figure 24: Experimental set-up for backfill test with dry granular materials

Full-scale 30 m long mockup for grout backfill

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.

The main components of the mockup are (**Figure 25**):

- 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; a 102° angle determines the mechanical support of the Supercontainers by the left and right floor sockets; 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)
- 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; in total, the heater capacity is 25 kW)
- 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; 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 mockup 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.

A water tightness 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. No leaks were detected and the water was let down in January 2008. A layer of insulation material was placed around the mockup to prepare it for the heated phase.

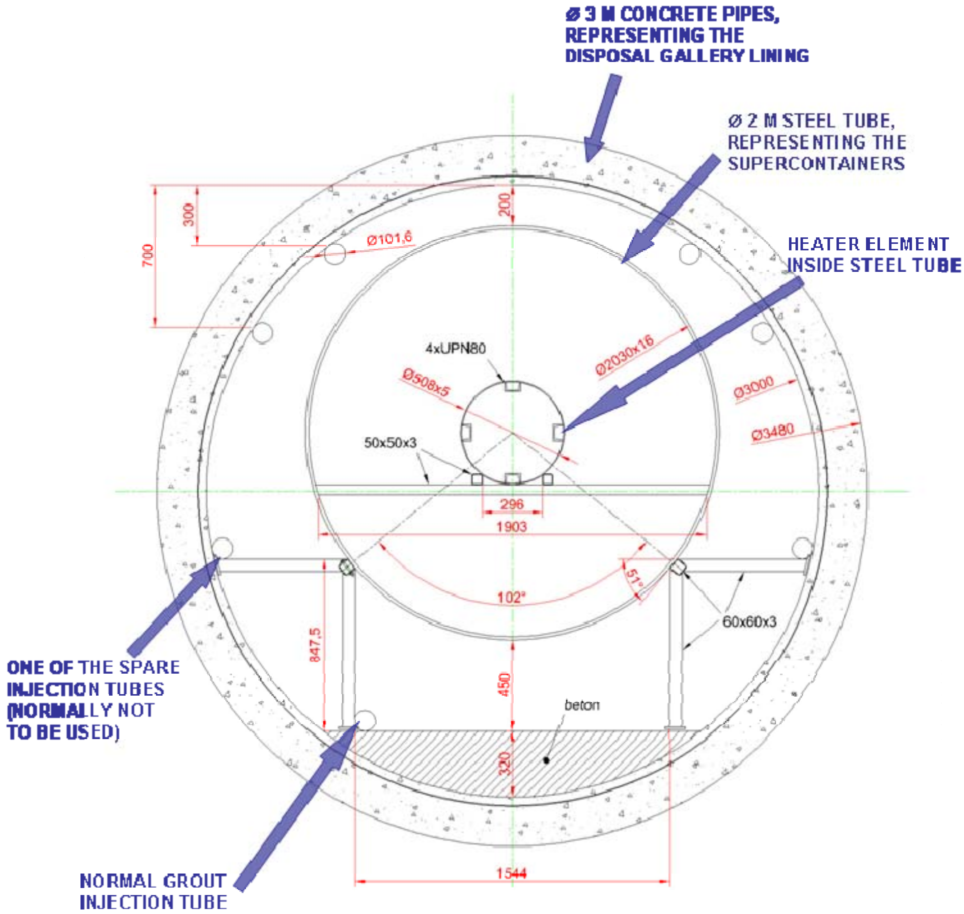


Figure 25: Radial cross-section of the full-scale 30 m long mockup for grout

2.2.7 Execution of the tests

Test on the reduced-scale mockup for grout backfill

On June 30th 2006, the grout injection backfill technique was tested on a 5 m long, reduced-scale (2/3rd scale) mockup of a disposal cell. The center of the mockup was equipped with a heater, representing the waste, locked in a steel tube filled with sand to simulate the Supercontainer and its thermal inertia. The initial average temperature of the tube surface was a stable 40°C. It took about 100 minutes, at a target rate of 5 m^3/h, to fill up the annular void.

After the setting of the grout, the result was investigated by means of taking borehole samples and cutting a slice of the mockup (see **Figure 26**). It was noticed that a 100% void filling with a homogeneous backfill had been achieved. Based on the above, it was concluded that the test had been a full success.

The following characteristics of the backfill were measured on the borehole samples:

- density: 2190 kg/m^3
- thermal conductivity: 3 W/°C-m (if 9% water content), 1.6 W/°C-m (if dried)
- compressive strength: 12 MPa

Figure 26: Reduced-scale mockup for grout backfill testing, after slice-cut (Nov. 2006)

Test on the reduced-scale mockup for granular materials backfill

All selected backfill materials were tested between June and October 2006. Borehole samples were taken from the resulting backfill. It was observed that the machine operated without failure under mechanically very harsh conditions, and achieved a linear pace of about 2 to 3 m/h. No problems with dust generation or water runback were encountered. The annular void was 100% filled with a backfill which was relatively homogeneous in terms of density and water content and which exhibited a relatively steep and regular slope, although generally the result was more positive for the bentonite-based materials than for the sand-based materials. Based on the above, it was concluded that the test had been a success.

Measured results are summarized in Table 4. The thermal conductivity is relatively low for some cases and probably on the edge of what would be acceptable. The tests did not address the issue of chemical compatibility with the Supercontainer concept.

Table 4: Summary of measured operational and materials data in the dry-gun backfill tests

Tested material	**Density** [kg/cm3]	**Water content** [%]	**Thermal conductivity** [W/m-°C]	**Compression strength** [MPa]
Pure sand *(SiO_2)*	not measured (but typically 2.1 saturated and 1.6 dry)	not measured	not measured (but typically 2.7 saturated and 0.35 dry)	not applicable
Sand/cement *(90 / 10)*	comparable to pure sand	7.0	2.944 ± 0.133	not measured (but typically 2 to 5 MPa)
Pure bentonite *(MX-80)*	1.391 1.043 (dry)	33.4	0.619 ± 0.011	0.200
Bentonite/sand *(75 / 25)*	1.442 1.092 (dry)	32.0	0.842 ± 0.017	0.110
Bentonite/cement *(85 / 15)*	1.528 1.131 (dry)	35.1	0.653 ± 0.016	0.670

Test on the full-scale 30 m long mockup for grout backfill

On April 8th 2008, the grout injection backfill technique was tested on a 30 m long, full-scale mockup of a disposal cell. This time, the heater inside the sand-filled tube was set to obtain an initial average tube surface temperature of 60°C. It took about 6 hours, at an average rate of 15 m^3/h, to fill up the annular void.

After the injection, the heater inside the mockup was left on semi-automatic control for 2.5 weeks after the injection. Another 2 weeks later, 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. As already observed in the reduced-scale tests, there was no visible effect of the cement hydration heat.

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.

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.

In September, small boreholes drilled through the back-end lid confirmed the fact that the backfill was still paste-like. However, it also provided 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, as was done with the reduced-scale mockup for grout. **Figure 27** and **Figure 28** 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 measurement 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.

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

Figure 28: Close-up of the flat front of already hard backfill material (status March 2006)

2.2.8 Evaluation of results and summary of conclusions

Both the grout and the dry-gun **technique** are operationally feasible for achieving a 100% backfilling of a HLW disposal drift within the Supercontainer disposal concept. For both techniques, it was possible to perform the backfill operations at a sufficiently rapid rate, without any malfunctions and with little or no dust generation or water runback. What remains to be demonstrated from an operational perspective is how the logistical needs behind the backfilling operations can be satisfied in actual underground repository conditions.

Concerning the compliance of the used backfill **materials** with their requirements, the following was concluded:

- Although the **backfill grout** did become hard as anticipated in the reduced-scale test, this was clearly not the case in the full-scale test. After reviewing the possible causes of this difference, 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. 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 was therefore concluded that the W/C ratio of the specific grout will need to be reduced in the next phases of the development process, to ensure that the grout becomes hard after injection.
- The **bentonite-based backfill materials** exhibit a low thermal conductivity concern that should be evaluated further through computer simulations and demonstration testing. Moreover, bentonite has some adverse characteristics with respect to the corrosion of steel. Hence, it should also be proven, through laboratory analysis, computer simulations and experimental testing, that the chemical boundary conditions for the waste overpack resulting from the use of the bentonite-based backfill material, are acceptable within the Supercontainer disposal concept.
- The **sand-based materials** tend to have a low cohesion. This will require fine-tuning of the actual granulometry. The thermal conductivity is generally high enough, provided that the emplaced backfill does dry out in the thermal phase (the arrival of the peak of the thermal pulse should be a matter of 5 to 20 years after disposal). The latter needs to be demonstrated, through computer analysis and demonstration testing.

In general, all tested backfill materials exhibit a mechanical strength that will not needlessly impair a hypothetical retrieval of the waste, as was part of the requirements definition (see Section 2.2.2).

2.3 Granular buffer in combination with prefabricated blocks (by NAGRA)

2.3.1 Logic of project implementation and planning

The main functions of the bentonite buffer are recalled below:

- *Confinement and attenuation;* the engineered barriers have to contribute through their physical and geochemical properties to the key safety functions of the repository system;
- *Initial complete containment for SF and vitrified HLW*; the design should ensure substantially complete containment of the radionuclides associated with spent fuel and vitrified HLW for a period of a thousand years or more;
- *Redundancy*; a cautious approach should be adopted in the choice of barriers and the dimensioning of particular components of the EBS. There may be barriers or processes that only make a significant contribution to safety if some parts of the system do not perform according to expectations;
- *Avoidance of and insensitivity to detrimental phenomena*; through an adequate choice of materials and a careful design;
- *Reliability of implementation*; the site and design should be selected such that the properties that favor safety can be relied upon to exist when the repository is implemented, without placing excessive demands on novel engineering technology and allowing for reliable quality assurance;
- *Reliability of closure of the repository*; the repository must be designed in such a way that it can be sealed within a few years;
- *Predictability*; in order to favor the predictability of their evolution, the engineered structures of the repository should preferably employ simple, well-understood materials.

For SF and vitrified HLW, the engineered barrier system comprises:
- dissolution-resistant waste matrices, incl. SF (MOX, UO_2 and Zircaloy clad) and HLW glass;
- corrosion-resistant canisters (steel);
- a layer of low permeability bentonite buffer surrounding the canisters, that slows groundwater movement around the canisters to negligible levels, and sorbs radionuclides and retards radionuclide transport when the canisters eventually fail.

In addition to the engineered barriers mentioned above, several seals or plugs will be constructed at strategic positions to limit the flow of water through the repository.

These functions lead to a series of required values for the main characteristics of the buffer, as summarized below.

2.3.2 Input data and functional requirements

The engineered barriers, which employ large quantities of material with favorable and well-known properties and predictable performance, provide the primary containment of the waste. After canister failure, the bentonite will be a very effective barrier and therefore, it is expected that most radionuclides will decay to insignificant levels within the engineered barriers. In the case of vitrified HLW and SF, the canisters are placed in tunnels surrounded by a bentonite buffer which has the following functions:

- to keep the canisters in place and protect them by homogenizing the stress field;
- to mechanically stabilise the rooms;
- to act as a transport barrier for radionuclides and a barrier for colloids;
- to provide a suitable geochemical environment;

- to ensure low corrosion rates of both canister and waste form;
- to limit microbial activity;
- to prevent human intrusion.

In order to provide these functions, it is necessary that at least a significant part of the bentonite is not altered in an unacceptable way by temperature or chemical interaction with the formation water, rock or corrosion products of the canister. To achieve these functions in a desired way, a number of predefined requirements have to be fulfilled (Table 5).

Table 5: Summary of functions and constraints related to buffer in NAGRA disposal concept

FUNCTIONAL REQUIREMENTS **related to the disposal tunnel BUFFER in NAGRA's disposal concept**		
FUNCTIONS		
Description of Objective	**Time Frame of Objective**	**Associated Material Parameters and Criteria**
Prevent human intrusion	After closure of emplacement tunnel (immediately after emplacement)	Design of seals
Mechanical stabilisation of the excavation after the failure of the support system and to limit the convergence of the emplacement tunnels		**Density of buffer ≥ 1350 kg/m^3** (bentonite bulk dry density at emplacement) Swelling potential of the buffer Creep behavior of the Opalinus Clay In-situ stress and pore pressure
Mechanical protection of the canister to keep the canister in the centre of the tunnel, to avoid deviatory stresses or point loads on the canister and to attenuate deformations caused by tectonic events	**Before canister loss of integrity**, i.e. $10^3 \ldots 10^4$ years	Viscosity of buffer
Suitable geochemical environment to avoid undesirable chemical effects on the buffer and to control or minimize corrosion of canisters and the dissolution of the waste form.	**After canister loss of integrity** i.e. > a few thousand years	pH of buffer and support material **Hydraulic conductivity ≤ 10^{-12} m/s** (after swelling of the buffer)
Transport barrier for radionuclides by limiting the advective flow through the barrier and providing high sorption and retention capability		**Hydraulic conductivity ≤ 10^{-12} m/s** (after swelling of the buffer) **Density of buffer ≥ 1350 kg/m^3** (bentonite bulk dry density at emplacement) Swelling capacity Sorption Diffusion coefficient
Compartmentalization of emplacement tunnel to effectively separate canisters from each other to increase robustness of the system		Radial and axial thickness of buffer
CONSTRAINTS		
The buffer should allow gas to escape (as long as steel parts are present)	**After re-saturation** of buffer and host rock	Swelling pressure Gas permeability
The buffer should behave as an adequate thermal conductor to limit the maximum temperature and avoid undesirable mineralogical changes or cementation of the buffer	**At all times**	Thermal conductivity ≳ 0.4 W/m/K (conductivity is function of density and water content)

2.3.3 Studies and computer modeling

In principle, emplacement techniques could be studied in numerous full-scale laboratory experiments, but these tests are time consuming and provide limited in-sight only into the emplacement process. Therefore, it has been decided to carry out numerical simulations first, before the approach is verified by physical testing of the emplacement.

Classical numerical approaches, so-called mesh-based methods, fail to model the required process. The so-called mesh-free methods (e.g. the Discrete Element Method or the Smoothed Particle Hydrodynamics Method), strongly developed within the last years, now offer unique capabilities to simulate processes of particle or aggregate transport, flow, compaction, mixing, separation and disintegration. In the ESDRED project the Particle Flow Code PFC^{3D} from ITASCA was used for the numerical simulations described here below.

Computer simulations to determine optimum particle size/shape/roughness distribution of backfill

The accessible density of the backfill material is a function of particle size distribution, particle shape and particle roughness as well as the procedure of backfilling. Within a parameter study, optimum constellations with respect to particle size, shape and roughness were determined assuming realistic mechanical boundary and initial conditions, derived from the proposed technology of backfilling.

PFC^{3D} models the interaction of particles on the micromechanical level, using contact laws with micromechanical parameters, which describe the force – displacement – relation at the contact. Since the micromechanical parameters are not directly related to the macroscopic parameters, numerical lab tests are used to calibrate the micromechanical parameters such that the macroscopic behaviour of the real material can be reproduced. Here, numerical shear box experiments were performed to calibrate the micromechanical parameters.

Computer simulations to evaluate different backfilling technologies

Besides the particle parameters, the backfilling procedure plays an important role, especially segregation can lead to increasing and non-acceptable void ratios.

Therefore, effective technological measures to avoid segregation have to be investigated by modeling different technological solutions for the emplacement via augers:

- Different geometrical setups of the tunnel system with installations, i.e. model with and without a gap between the waste canister and the tunnel face
- Different particle size distributions of the buffer material
- Different filling technologies with respect to the movement of the auger

These simulations were used to derive optimum technological parameters. In addition, sensitivity studies have been carried out to evaluate the influence of different geometrical conditions (e.g. distance between different canisters, filling of this gap between canisters with bentonite blocks or granular material).

The evaluation of the results of all above described computer simulations led to the main conclusion that the backfill material used for testing should be the **Fuller-type material (0-10 mm) with a Bi-modal distribution.**

Details of these simulations are described in NAGRA Working Report NAB 06-02 [18].

2.3.4 Laboratory testing

A general analysis of the MX-80 bentonite was performed to characterize its chemical and mineralogical properties (clay phases, main and accessory minerals) and to identify any changes in these during pelletisation. The measurements were carried out on the bulk material.

The raw Na-bentonite MX-80 (Wyoming bentonite from Amcol Speciality Minerals) was delivered in a conditioned (slightly granulated) state to improve the pourability and pelletising behaviour. The C_U (3.8) and C_C (1.0) calculated from the sieve curve are far from the values of the Fuller curve and low values for the poured bulk density were expected. The pipette analysis of the size distribution of the clay particles show a content of more than 80% clay fraction for both samples (Table 6).

Table 6: Grain size distribution (pipette analyses)

Bentonite	> 63 µm	< 20 µm	< 2 µm
MX-80 Amcol	3.76%	86.46%	81.55%
Granulate run E	3.30%	92.51%	87.44%

The measured poured bulk density of the MX-80 Amcol bentonite was 1.11 g/cm^3 and was recalculated to a dry density of 1.00 g/cm^3 (water content 10.80%). The vibrated maximum bulk density was 1.30 g/cm^3 and the corresponding dry density 1.17 g/cm^3. A specific solid density of 2.674 g/cm^3 was determined with the He pycnometer.

The bulk grain density of the small bentonite granules, determined using mercury intrusion porosimetry, was 1.43 g/cm^3 and was recalculated to a dry density of 1.29 g/cm^3. The total porosity of the granules was 48.8%.

After the bentonite had been stored in the laboratory at an elevated relative humidity of 75%, the water content of the bentonite increased to 15.0% for the MX-80 Amcol and to 16.9% for the bentonite granulate run E. For a lower relative humidity (22%), the water content was 6.4% and 4.9% respectively. From this amount of adsorbed water, a total surface area of the bentonite of 591 m^2/g can be calculated for the bentonite MX-80 Amcol and 523 m^2/g for the bentonite run E. The specific (outer) surface area determined by N_2-adsorption measurements (BET) was 44.6 m^2/g for the bentonite MX-80 Amcol and 33.1 m^2/g for the bentonite run E.

The two bentonites have a similar mineralogical composition (see Table 7). A mean layer charge of 0.28 was determined for the montmorillonite and a cation-exchange capacity of 74 meq/100 g montmorillonite was measured. Determination of the exchangeable cations show 52.4 meq Na/100 g, 13.2 meq Mg/100 g and 1.4 meq K/100 g. The measured content of Ca (32.2 meq/100 g) is too high and is caused by soluble Ca-containing phases (calcite).

Table 7: Rietveld analysis of mineralogical composition (in wt% with absolute errors)

	MX-80 Amcol wt%	Bentonite run E wt%
smectite	85.7 ± 1.2	84.9 ± 1.2
muscovite	4.6 ± 0.8	4.8 ± 0.8
quartz	3.4 ± 0.5	3.7 ± 0.5
feldspar	5.2 ± 0.8	5.2 ± 0.8
calcite	1.0 ± 0.2	1.3 ± 0.2

2.3.5 Test program definition

The objectives of NAGRA's bentonite emplacement testing program within the EC-supported project ESDRED were as follows:

- Testing and demonstrating of suitable granular buffer installation techniques on a full scale in surface facilities;
- Verification if the requirements can be fulfilled.

The general objectives and the experiences from previous experiments lead to an ambitious project specific target value for the emplacement dry density of about 1500 kg/m^3. In previous experiments NAGRA executed various tests with different bentonite types for buffer material. Because of its favourable properties with respect to the technical emplacement, bentonite granulate is used in NAGRA's reference concept. Although small-scale laboratory experiments were performed several years ago, a large scale test was felt to be advantageous to improve confidence that the required dry density of emplaced bentonite granulate can actually be reached.

2.3.6 Set-up of the test facility

Equipment considerations

Three types of equipment were evaluated for the emplacement tests of granular bentonite, namely conveyer, pneumatic and auger method. Based on equipment evaluation trials the auger technique had been identified as preferred method. As first optimization within the ESDRED project it was decided to develop a twin auger system, instead of the previously used single auger system. For this task the company "Rowa Tunneling Logistics AG", Wangen, Switzerland was contracted to plan, construct and test such a new emplacement system.

The built auger has a total length of about 9 m and a weight of 1350 kg. The length of the two auger casings is 7.0 m, the diameter of the tubes are 0.2 m. The feed rate can be controlled by the auger turning speed. The rotating screwing motion of the auger moves the bentonite material to the end of the outer casing tube where it either falls off the end of the auger freely or can push the material out into the existing bentonite mass. The maximum feed rate is actually 7 m^3 of granular bentonite material per hour. **Figure 29** gives a photograph of the used Twin auger system.

Figure 29: Photograph of the Twin auger system during the inspection in the workshop

In the EB project, a wooden model representing only the upper part of the tunnel situation was used for the emplacement test experiments. For the ESDRED project we wanted to have a more realistic and more robust steel model with a round shape representing the full tunnel situation. But for easier handling and for performing more tests in the given time we reduced the scale of the model by 20% (1:1.25; from 2.5 to 2.0 m diameter). A second improvement with the steel model was the possibility to have 11 openings around the surface of the model for sampling and analyzing the geotechnical bentonite parameters as water content, grain size distribution and emplacement density.

The model representing the tunnel situation with a dummy canister on the bentonite blocks was constructed from steel. The left photo (a) of **Figure 30** shows the outside view of the model from the back; the right photo (b) provides a look inside into the model where the dummy canister and the slope of the backside are visible.

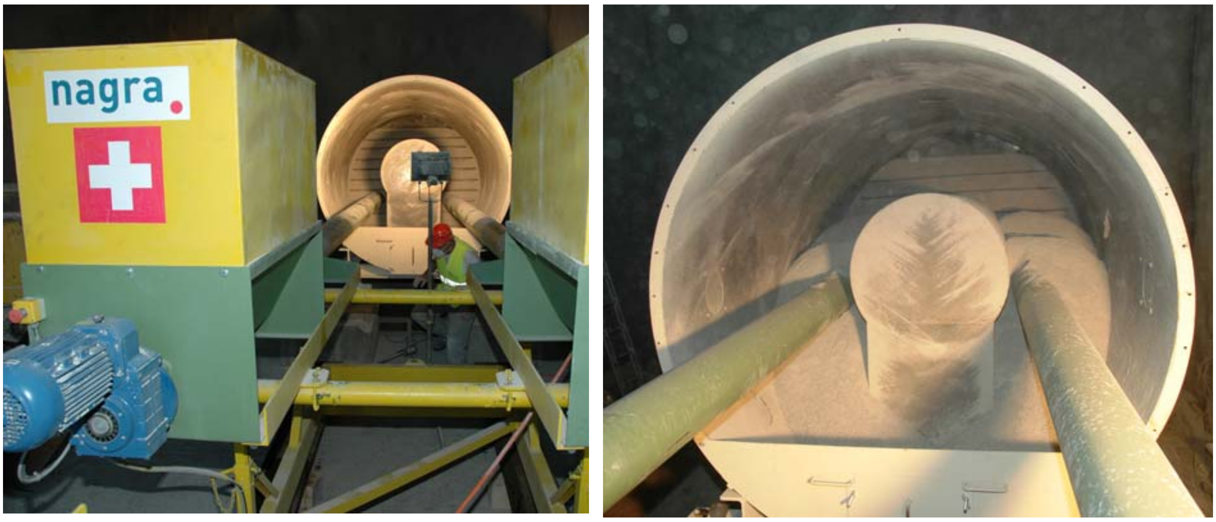
The steel model was backfilled with granular bentonite material using the Twin auger system (see **Figure 31**). The accurate volume of the steel model has been determined by the company FLOTRON AG (Engineers for Surveying, Photogrammetry and Civil Engineering). This number is quite important for the calculation of the final emplacement density. To fix the precise volume of the steel model, the model was split into regular volumes (like cylinders and cubes). To check the model on differences and irregularities, they scanned the surfaces with a laser-range theodolith. The calculation of the volume was made by regular volumes with the true dimensions from the surveying. The detected irregularities were considered.

The result of the volume determination was the following:

- Total filling volume: 7.21 m^3
- Accuracy: ±1%

(a) (b)

Figure 30: Photographs of the empty steel model - whole model (a) and annular gap (b)



(a) (b)

Figure 31: Photographs taken during emplacement of the granular bentonite

Granular material considerations

For the EB project, the bentonite for the blocks, originally produced for the FEBEX experiment at Grimsel Test Site, were obtained from a Spanish quarry near Almeria, the so called “Serrata bentonite”. Therefore, the same material was used for the production of the pellets. In preparation for the EB experiment NAGRA undertook several tests with “Calcigel bentonite” provided by Südchemie, Germany. The production of the granulated material was done in the Rettenmaier facilities in Holzmühle, Germany. For the ESDRED project, neither the proposal nor the contract documents did specify where the bentonite materials were to come from. NAGRA decided to use Wyoming bentonite MX-80 from Amcol Chemicals (United Kingdom). MX-80 is one of the best studied and characterized bentonites.

The purpose of this section is to describe and present the results of the individual actions that were taken from February 2005 through July 2006 within the ESDRED project, leading up to the production of suitable granular bentonite material for the emplacement tests.

The sodium-bentonite MX-80 was delivered from Wyoming via the United Kingdom in a conditioned, slightly granulated state to improve the pourability and pelletizing behaviour. The calculated parameters of the sieve curve are far from the values of the Fuller curve. Low values for the pour bulk density were expected. The determined pour bulk density was 1.11 g/cm^3 and recalculated to the dry density 1.00 g/cm^3 (water content 10.8%). The vibrated maximum bulk density was 1.30 g/cm^3 and the calculated dry density 1.17 g/cm^3. The bulk density of the small bentonite granules, determined with MIP was 1.43 g/cm^3 and recalculated to the dry density 1.29 g/cm^3. The total porosity of the slightly granulated bentonite material was 48.8%.

Pelletizing experiments with pure bentonite material and with admixtures of sand were carried out at the TU Bergakademie Freiberg (Germany) and at Rettenmaier AG (Germany). The produced granules were analyzed in the IGT ClayLab of ETH-Zürich for their bulk density, water content and porosity. During pelletization of the bentonite, an increase of the bulk grain dry density from 1.17 g/cm^3 to 2.10 g/cm^3 with simultaneous halving of porosity was achieved.

Table 8 summarizes the obtained pellet density and porosity. The densities of the produced bentonite briquettes were found as very inhomogeneous. The outer zone was hard and showed a higher density and lower porosity. The inner zone was soft and showed a remarkable lower density. The size of the briquettes seems to be too large for a homogeneous compaction.

The coarse fraction of the granular bentonite material was rounded before it was used for the emplacement experiments. The rounding improved the flowability and produced a better-graded grain size distribution and therefore a higher emplacement density. The rounding was carried out by blowing the granular bentonite with air pressure through a 200 m long steel pipe with a conventional shotcrete gun. Table 9 summarizes the bulk density, water content and medium grain size before and after rounding. **Figure 32** shows the effect of rounding on the shape of the granules.

The emplacement tests were performed with certain mixtures of coarse and fine granulates. Table 10 gives the bulk density, water content and grain size of the bentonite fine fraction.

Table 8: Bentonite densities and porosities

Sample	**grain wet density ρ**	**grain dry density ρ_d**	**water content**	**total porosity**	**average pore radius**
	g/cm^3	g/cm^3	%	%	nm
Pretests Rettenmaier & Söhne					
pure bentonite (Kunigel V1)	2.065	1.992	6.95		
bentonite plus 25% quartz sand 0.1-0.5 mm	2.155	2.052	4.78		
bentonite plus 25% quartz sand <0.1 mm	2.017	1.930	4.31		
bentonite plus 50% quartz sand 0.1-0.5 mm	2.247	2.163	3.73		
Pretests University of Freiberg					
pure bentonite (MX-80)	2.200	2.104	4.55	14.20	5.96
bentonite plus 30% quartz sand 0.1-0.5 mm	2.171	2.115	2.65	16.39	6.03
Rettenmaier & Söhne Pellets pure MX-80 (used for the emplacement tests)					
AB1 material before test A (fraction >0.5 mm)	2.207	2.099	5.10		
Z fine admixture (0.5-1.5 mm)	2.107	1.999	5.40	20.32	6.47
EB material before test E (fraction >0.5 mm)	2.070	1.962	5.48	16.29	5.26
BR coarse briquettes	1.896 (1.73-2.05)	1.802 (1.65-1.95)	5.22	23.49-18.03	10.37-7.99

Table 9: Bulk density, water content and medium grain size before and after rounding

Sample	ρ	ρ_m	w	ρ_d	ρ_{md}	d_{50}
	g/cm^3	g/cm^3	%	g/cm^3	g/cm^3	mm
granular bentonite coarse fraction	1.20	1.36	5.0	1.15	1.30	3.234
V1 rounded (200 m)	1.33	1.55	5.2	1.26	1.47	3.137
V1 fraction <2 mm	1.43	1.59	5.1	1.36	1.51	
V2 rounded (100 m)	1.44	1.49	5.2	1.36	1.41	3.258

With: ρ = bulk density / wet density [g/cm^3] of loosely filled material from 50 cm height

ρ_m = bulk density / maximum wet density [g/cm^3] of vibrated material on a sieve shaker table

w = water content [%] in weight-% of dried material

ρ_d = dry density [g/cm^3] of loosely filled material from 50 cm height

ρ_{md} = dry density / maximum dry density [g/cm^3] of vibrated material on a sieve shaker table

d_{50} = median grain size

Table 10: Density, water content and grain size of granular bentonite fine fraction (0.5-1.5 mm)

Sample	ρ	ρ_m	w	ρ_d	ρ_{md}	d_{50}
	g/cm^3	g/cm^3	%	g/cm^3	g/cm^3	mm
granular bentonite fine fraction	1.10	1.21	5.10	1.05	1.16	0.824

Figure 32: Changes in grain shape before (left) and after (right) the rounding process

2.3.7 Execution of the tests

In July 2006, over a two week period, 6 emplacement tests (A to E) were executed. The first emplacement test (A) was carried out with rounded coarse granular bentonite without any additions. The material was removed after filling was finished and refilled in "big bags". This material was then mixed on site with different amounts of the fine fraction for the next filling runs.

Before the last filling run E, coarse unrounded bentonite briquettes (grain size up to 40 mm, on site water content 4.8 %) were added. The runs C, D and E were carried out twice (repeat runs, code w).

In all, the following emplacement tests were performed:

- A : 100% coarse granulates
- B : 92.3% coarse granulates, 7.7% fine granulates
- C : 85% coarse granulates, 15% fine granulates
- Cw : 85% coarse granulates, 15% fine granulates (same material as run C)

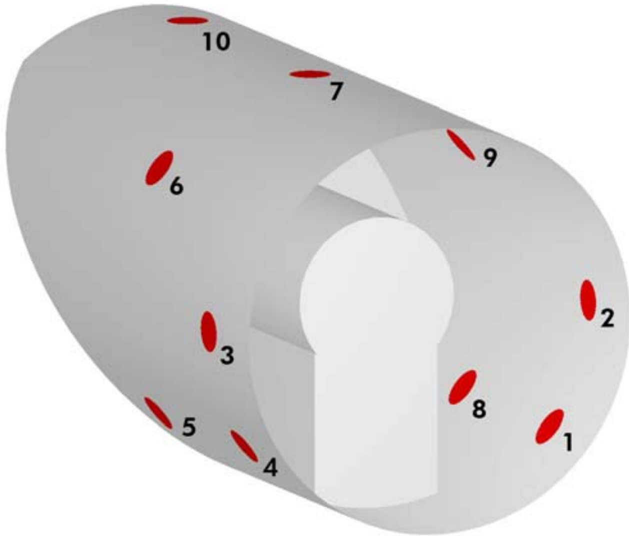
  This was a repeat run.
- D : 70% coarse granulates, 30% fine granulates
- Dw : 70% coarse granulates, 30% fine granulates; repeat run (same material as run D)

  This was a repeat run. In run D, some technical problems occurred with the optimal auger position, so the emplacement densities of this test are not representative for this material mixture. We decided to repeat this test with the same material.
- E : 64.1% coarse granulates, 27.5% fine granulates, 8.4% very coarse briquettes
- Ew : 64.1% coarse granulates, 27.5% fine granulates, 8.4% very coarse briquettes (same as run E

  This was a repeat run, but with a slightly different emplacement procedure. Instead of emplacing the material in layers as in the runs before, in run Ew only one layer was filled in. The auger position was kept at the top, close to roof.

As part of the testing, a comprehensive laboratory testing program was executed to investigate the performance of the system. Bentonite samples were taken sequentially from the "big bags" before filling for grain size distribution, water content and bulk density. After every backfill operation of the model, the following parameters were investigated:

- global bulk density
- local densities at 11 predefined points at the outer surface of the steel model;
  Ten of the sample points are shown on **Figure 33(a)**. The eleventh sample was taken from the backside (see **Figure 30**). The taking of samples is illustrated by **Figure 33(b)**.
- particle size distribution measurements of the granular bentonite material before and after emplacement at selected points at the outer surface of the steel model
- water content measurements of the granular bentonite material before and after emplacement
- other properties of the granular material as mineralogy, swelling pressure, thermal conductivity, etc. will be as well determined at this ESDRED samples. But this analyses will be directly financed from NAGRA



(a)

(b)

Figure 33: 3D view of the steel model with sampling locations (a) and sampling itself (b)

Measurements before filling

Bentonite samples were taken sequentially from the "big bags" before filling for grain size distribution, water content and bulk density. Table 11 provides a summary of the bulk densities and water content before filling (see Table 9 for explanation of symbols).

Table 11: Average values and span of bulk density and water content of bentonite before filling

Bulk material	ρ	ρ_m	w	ρ_d	$\rho_{m\,d}$
	g/cm^3	g/cm^3	%	g/cm^3	g/cm^3
Bentonite A (bulk)	1.53 (1.49-1.58)	1.70 (1.62-1.81)	5.15 (5.1-5.2)	1.46 (1.41-1.51)	1.61 (1.54-1.72)
Bentonite B (bulk)	1.54 (1.52-1.57)	1.69 (1.65-1.76)	5.18 (5.10-5.40)	1.47 (1.44-1.49)	1.61 (1.57-1.67)
Bentonite C (bulk)	1.53 (1.51-1.54)	1.69 (1.66-1.74)	5.32 (5.30-5.40)	1.45 (1.44-1.47)	1.61 (1.58-1.65)
Bentonite Cw (bulk)	1.55 (1.53-1.57)	1.74 (1.73-1.77)	5.30 (5.20-5.60)	1.48 (1.45-1.50)	1.66 (1.64-1.69)
Bentonite D (bulk)	1.52 (1.50-1.54)	1.70 (1.66-1.73)	5.38 (5.30-5.50)	1.44 (1.42-1.46)	1.61 (1.58-1.64)
Bentonite Dw (bulk)	1.52 (1.48-1.53)	1.71 (1.68-1.73)	5.50 (5.40-5.60)	1.44 (1.40-1.45)	1.62 (1.59-1.64)
Bentonite E (bulk)	1.56 (1.55-1.57)	1.73 (1.70-1.75)	5.46 (5.40-5.60)	1.48 (1.47-1.49)	1.64 (1.61-1.66)
Bentonite Ew (bulk)	1.55 (1.53-1.57)	1.72 (1.71-1.75)	5.66 (5.50-5.80)	1.47 (1.45-1.49)	1.63 (1.62-1.66)

Measured bulk density after filling

After each emplacement test, the bulk density of the whole silo emplacement was measured. The bulk density is the net weight of buffer material over total volume of the test section. Table 12 summarizes the measured bulk densities after emplacement. The results in this table are as well graphically reflected in **Figure 34**.

The bulk densities of the granular bentonite material show only small changes for different admixtures of fine granular bentonite and bentonite briquettes. The water content increased only slightly during the test runs from 5.0 % to 5.8 %. The results are very promising as the required densities can be reached reliably (see NAGRA report NAB 07-24 [9])

Table 12: Bulk densities of the whole silo emplacement

charge		bulk wet density	w	bulk dry density
		g/cm^3	%	g/cm^3
A	100% coarse rounded granular material	1.457	5.1	1.386
B	92.3% coarse, 7.7% fine	1.558	5.2	1.481
C	85% coarse, 15% fine	1.556	5.3	1.478
Cw	85% coarse, 15% fine; repeat run	1.554	5.2	1.477
D	70% coarse, 30% fine	1.521	5.4	1.443
Dw	70% coarse, 30% fine repeat run	1.560	5.5	1.479
E	64.1% coarse, 27.5% fine, 8.4% briquettes	1.595	5.4	1.513
Ew	64.1% coarse, 27.5% fine, 8.4% briquettes Repeat run; only one layer, augers at top, close to roof	1.548	5.5	1.468

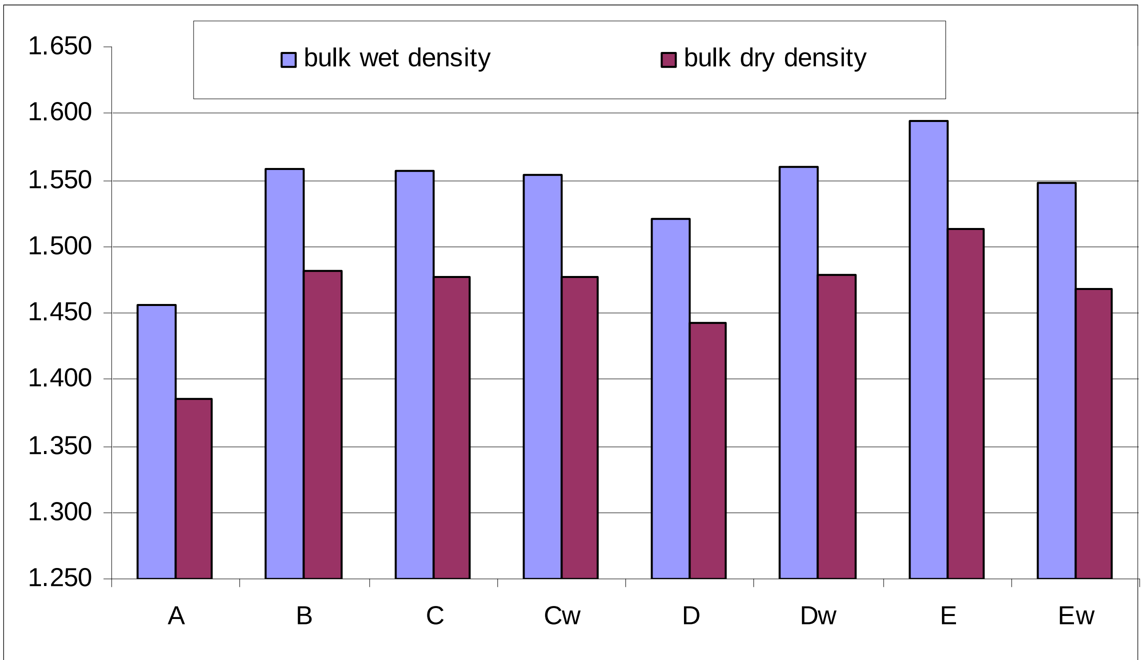


Figure 34: Bulk densities of the whole silo emplacement

2.3.8 Evaluation of results and summary of conclusions

As part of the testing, a comprehensive laboratory testing program was executed to investigate the performance of the system. The results were evaluated and compared to the predicted and required buffer parameters.

NAGRA is satisfied with the results of the work to date in producing a bentonite granular mixture that meets the original project expectations. The production done commercially to date demonstrated that the basic principles of agglomeration and compaction and adequate equipment already exist to create high density pellets of compacted bentonite. These can subsequently be ground and mixed to achieve emplacement densities of 1.5 g/cm^3 using powdered raw material with water contents in the range of 5 to 6 %.

With the existing test setup we could not sample the material for homogeneity (density and grain size distribution) inside the steel model. But we executed a lot of measurements on the material before filling and afterwards through eleven sampling points from the steel model outside. The homogeneity of the bentonite after mixing was quite good, of the samples somewhat less.

In theory the optimal emplacement densities can be reached with a bimodal grain size distribution with diameters 1:10 and a fraction of about 70% of the coarse material. In our test series we started off with the 100% coarse fraction, then we added in steps more and more of the fine fraction. Of course with 100% of the coarse fraction the reached emplacement was not very good. But after adding 15% of the fine fraction it improved quite a lot, and afterwards with further increasing the amount of fine material the increase in emplacement densities were not significant anymore.

Overall, our system of emplacement of granular bentonite mixture was very robust

The following aspects could be improved in the future:

- With further drying of the bentonite raw material to about 2 to 3%, instead of about 5%, it would be possible, if necessary, to increase the emplacement dry densities by 2 to 3%, but the technique to produce pellets with very low water content bentonite must be improved.
- In laboratory tests at ETH-Zurich we could demonstrate that adding about 25% of a very coarse fraction with granule diameters of 2 to 3 cm could increase the emplacement dry densities by about 5%, but the technique to produce large, homogenous high density pellets with low water content must be improved.
- The emplacement equipment will need some fine tuning in order to further improve the handling. On the basis of the developed twin auger system, a few years ago for the EB-Emplacement Tests at Mont Terri we used a single auger system, we could, if necessary, easily construct a system with four augers. A technical improvement would be the steering of the individual augers in all directions with hydraulic systems.
- Alternative buffer materials to Wyoming bentonite MX-80 will be studied in the future, for example within the framework of a NAGRA-SKB cooperation with the projects LOT (Long Term Test of Buffer Material) and ABM (Alternative Buffer Material) at the Aspö Rock Laboratory.
- We will study in the future as well the production and the behavior of sand / bentonite and possibly rock fragments / bentonite granulate mixtures

2.4 Seal performance testing (by GRS)

2.4.1 Logic of project implementation and planning

From the beginning, the successful execution of the SB experiment has been based on the sequential conduction of preceding laboratory investigations for the determination of most suited material mixtures and their specific material parameters, the conduction of mockup tests before going *in-situ* for testing seal material installation techniques and for checking the time periods needed to reach full seal saturation and for checking the numerical models used to design the in-situ experiments at the MTRL, and finally to conduct the in-situ experiments on basis of proven experimental techniques for demonstrating the seal function under representative in-situ conditions.

2.4.2 Input data and functional requirements

As already mentioned in Section 1.5.1 two alternative disposal concepts for two different types of high-level waste (HLW) are considered in Germany:

1. The borehole disposal concept considering the disposal of HLW steel canisters containing either vitrified fission products remaining from SF reprocessing or cut SF in deep vertical boreholes,
2. The drift disposal concept considering the disposal of Pollux steel casks containing non-reprocessed Spent Fuel assemblies in backfilled disposal drifts.

One function to be fulfilled by the sealing material is to act as a preferential pathway for gases, either being generated by anaerobic corrosion of the waste canister or by radiolysis of formation water in the dry state as well as in the saturated state. If the gas entry pressure as well as the break-through pressure of the SB material is kept sufficiently below the gas entry pressure of the host rock, high gas pressure in the disposal room will not develop.

Another function to be fulfilled on the long term is to provide sufficiently low permeability to water in the saturated state so that the migration of radionuclides out of the repository is hindered once being leached from the waste forms.

The aforementioned material properties seem to be contradictory, but can be achieved when using moderately compacted clay-sand mixtures as buffer material. Optimized material mixtures exhibit a high gas permeability in the unsaturated state and even after water uptake from the host rock they exhibit a comparably low entry and break-through pressure to gas. On the contrary, because of the swelling of the clay minerals after water uptake, the permeability to water in the saturated state is comparably low and hence, migration of leached radionuclides out of the disposal areas is diffusion controlled like in the undisturbed host rock.

2.4.3 Studies, computer modelling

Preceding both the above-mentioned mockup and in-situ experiments are scoping calculations performed to enable proper design of the experiments and to validate, at a later stage, the used codes and THM models by comparing modelling and test results. GRS applies the code CODE_BRIGHT developed by the Technical University of Catalonia (UPC) in Barcelona. Note that the GRS has used version 2.3 of the code for the calculations within ESDRED. Future calculations will most likely be done with version 3.0.

The Barcelona Basic Model (BBM) implemented in CODE_BRIGHT is an elasto-plastic model able to represent many mechanical features of unsaturated soils in a consistent and unified manner. In the framework of the project it was used for the assessment of the mechanical behaviour of the sealing materials and the Opalinus clay. Gas and water flow was modelled according to Darcy's law and the molecular diffusion of water vapour is governed by Fick's law. The mass of water vapour per unit volume of gas is determined via the psychrometric law and the solubility of air in water is controlled by Henry's law. The hydraulic parameters for the clay/sand mixtures such as relative permeability and capillary pressure as functions of saturation were established by extrapolation of the two-phase flow data obtained in the KENTON project and additionally validated through special laboratory saturation tests on small samples.

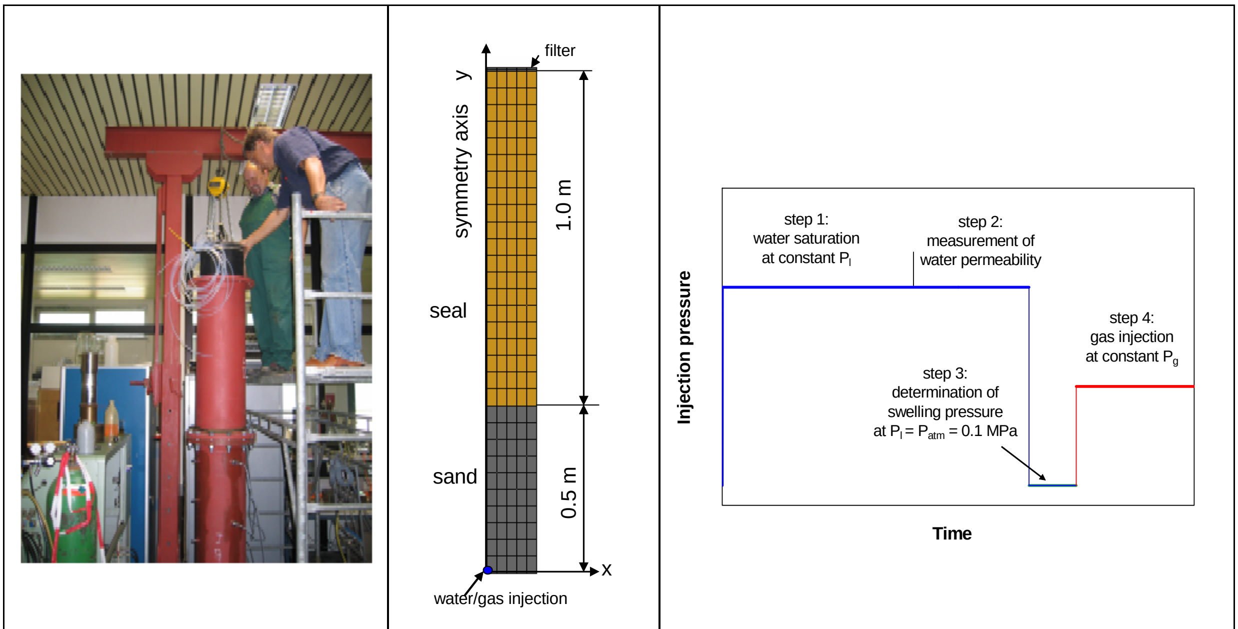
The scoping calculations for designing the tests have been conducted by using material parameters preliminarily determined during the preceding laboratory tests and taken from literature. The parameters for the Opalinus Clay were taken from the literature as well (see Zhang et al., 2004 [21]).

The calculations focused on prediction of testing conditions such as adequate injection pressures for water and gas, duration of water saturation, ranges of measuring parameters (gas and water flux, swelling pressure, total pressure etc.), and determination of initial and boundary conditions in the in-situ test field. In the scoping calculations, the materials installed in the mockup and in-situ tests were assumed as homogeneous and isotropic. Processes prevailing in the materials during the tests were considered as coupled THM processes, so that the following balance equations were to be solved: balance of energy, balance of water mass, balance of air mass, and balance of momentum (equilibrium).

As a first step of the test design activities, scoping calculations were performed to assess the time needed to reach full saturation in the mockup and in-situ experiments (see Rothfuchs et al., 2005 [21]).

Scoping Calculations for the Mockup Tests

The mockup tests are designed as a full-scale replica of the envisaged in the in-situ experiments. The only deviation from reality is the steel tube simulating the 0.31 m wide and 3 m deep test borehole at MTRL. **Figure 35** shows a photo of the mockup, the numerical model and the calculation steps used in the numerical simulation of the mockup test.



a) Photo of mock-up	b) FE-model	c) Test procedure

Figure 35: Photo (a), numerical model (b) and calculation steps(c) of the SB mockup

According to the foreseen test procedure the following steps were considered in the calculations:

- **Step 1:** Water injection at constant water pressure to determine evolution of water saturation and time needed for full saturation;
- **Step 2:** Water flow through the saturated seal at constant injection pressure and measurement of water outflow
- **Step 3:** Reduction of the water pressure down to atmospheric pressure to examine the swelling pressure (remaining total stress) in the seal;
- **Step 4:** Gas injection into the saturated seal at constant flow rate to determine gas entry/break-through pressure and gas outflow.

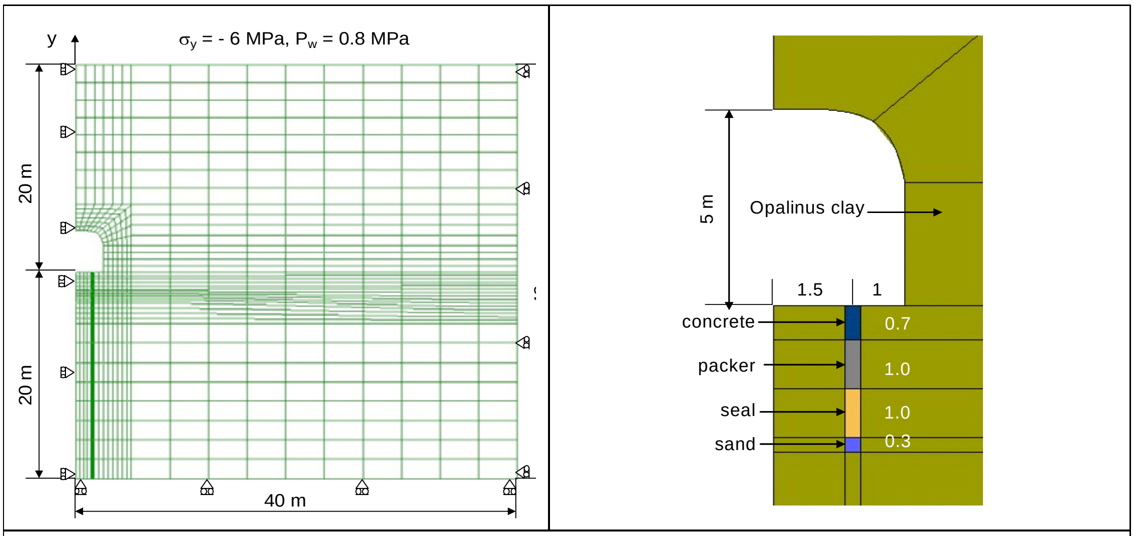
Scoping Calculations for the in-situ Experiments

Scoping calculations for the in-situ experiments were done to obtain an assessment of initial and boundary conditions and the duration of seal saturation under in-situ conditions. Due to excavation and ventilation of the test niche at the MTRL, the hydro-mechanical state of the surrounding rock is disturbed. Additionally, the THM conditions around the boreholes drilled down from the floor of the test niche (see **Figure 40** below) are to be assessed. During injection of water and gas into the seal, coupled hydro-mechanical processes will occur not only in the seal but also in the surrounding rock. The finite element mesh, the boundary conditions, and the different materials installed in the borehole are shown in detail in **Figure 36**.

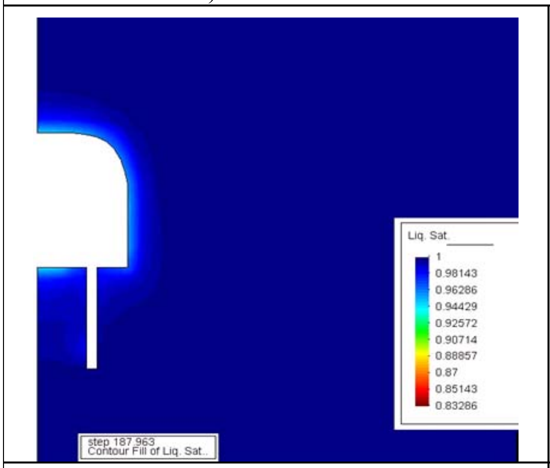
In the model, the materials were assumed homogeneous and isotropic. Both clay/sand mixtures with clay contents of 35% and 50% were considered in the calculations. Because of lack of data for the injection chamber, packer and concrete, the properties and mechanical parameters of the clay rock were used for them. However, a high permeability of 1E-12 m^2 was applied to the injection chamber, while the packer was assumed to be impermeable. Such simplifications are considered acceptable for the purpose of scoping calculations focusing on the determination of hydro-mechanical processes in the seal and surrounding rock.

In the calculations, the following in-situ conditions at the MTRL were taken into account. The temperature in the rock and in the niche is 17 °C for the initial state. A vertical total stress of 6 MPa applied on the top boundary and the gravity effect result in an initial vertical total stress equal to 6.48 MPa at the level of the niche floor. Assumption of a ratio $K_o = 0.77$ of effective horizontal stress to vertical stress leads to an initial total horizontal stress of 5.2 MPa at the floor level. A water pressure of 0.8 MPa supplied to the top boundary and its hydrostatic distribution in the model region result in an initial pore water pressure of 1.0 MPa at the floor level. An atmospheric pressure of 0.1 MPa was taken as the initial gas pressure. Flow of water and gas through the other boundaries is not allowed.

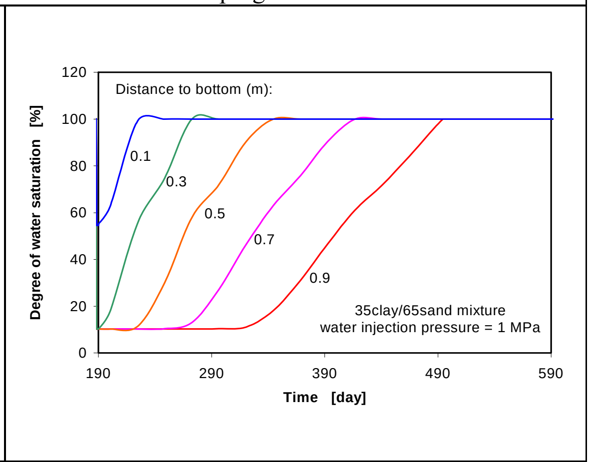
The hydraulic response of the rock mass to excavation and ventilation of the niche and borehole six months after niche excavation and eight days after borehole drilling results in a sudden reduction of the pore water pressure even to a negative value (suction) of –1 MPa. In contrast to this, highly concentrated stress near the lower corner of the borehole compresses the material and hence generates a high pore water pressure of up to 6 MPa. During ventilation with a relative humidity of 85 %, the pore water pressure reduces steadily. Six months later, the zone with negative pore water pressure extends to about 1 m from the niche wall into the rock mass. The borehole drilling induces an additional dilatancy of the surrounding rock and hence a further reduction of the pore water pressure. Due to excavation and ventilation of the niche and the borehole, the surrounding rock is desaturated. **Figure 36(b)** shows the respective distribution of water saturation in the surrounding rock at the end of borehole drilling and ventilation. The de-saturated zone with a water saturation level of less than 95 % is limited to 0.5 m to the niche wall. The de-saturation mainly caused by the dilatancy of the clay rock is not significant.



a) Numerical model and materials considered in the scoping calculations



b) Distribution of water saturation in the surrounding rock



c) Evolution of water saturation in a 35clay/ 65sand seal at an injection pressure of 1 MPa

Figure 36: Modelling of starting conditions of the SB in-situ experiment

After installation of the seal in the borehole, the water injection phase is simulated by applying a water pressure of 0.5 or 1 MPa to the lower porous chamber. **Figure 36(c)** illustrates the evolution of water saturation at some selected points in the 35clay/65sand seal at an injection pressure of 1 MPa.

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 mockup tests and 300 days for the in-situ experiment and for a 50/50 clay/sand-mixture 570 days for the mockup and 1050 days for the in-situ experiment for a seal length of 1 m and a water injection pressure of 1 MPa.

Generally, the modelling data indicated that - provided the modelling parameters can be realized *in-situ* reasonably - the required sealing function of the considered clay/sand-mixtures can be successfully demonstrated *in-situ*.

2.4.4 Laboratory mockup testing

Before going *in-situ*, both the installation techniques and the required saturation time for the material mixtures being considered were to be investigated and optimized in large-scale mockup tests in the above-ground laboratory at Braunschweig. The principle layout of the mockup is shown in **Figure 37**.

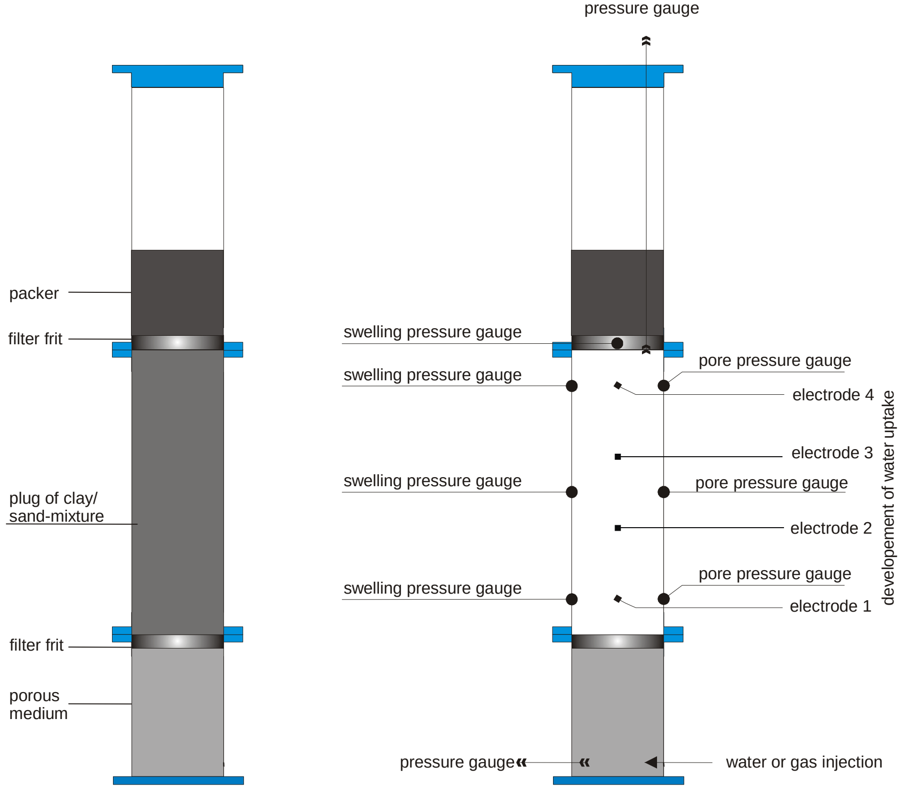


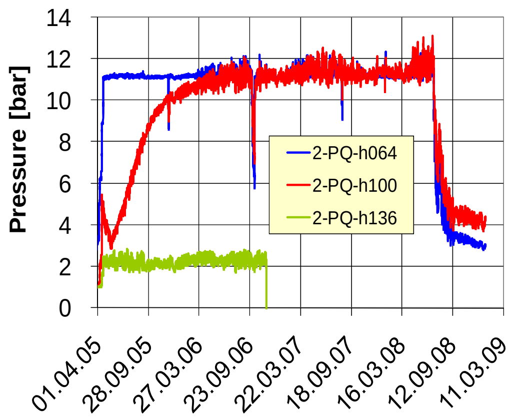
Figure 37: Principle layout of the SB mockup with the locations of measuring sensors

The mockup tests are designed as a full-scale replica of the envisaged in the in-situ experiments (**Figure 40** below). The tube length is 2.5 m and the sealing material is installed in thin layers of about 5 to 10 cm in a similar way as *in-situ*. Different techniques (hand stamping, vibrator technique) have been tested and the achievable density has been determined. Additionally, the gas permeability, the time required to achieve saturation, the water permeability, the gas entry/break-through pressures, and the gas permeability after the break-through are determined in the course of the test in order to provide adequate experimental data and experiences for the successful conduction of the in-situ experiments at the MTRL.

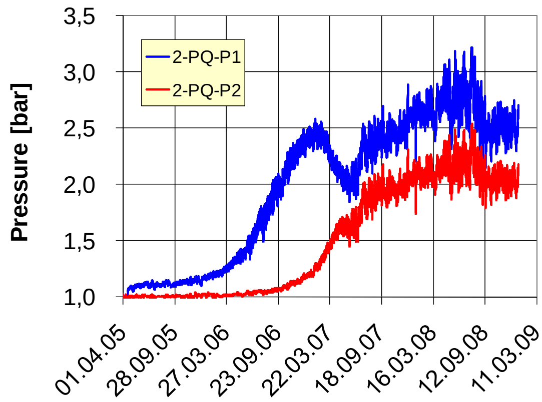
The detailed objectives of the mockup test were defined as follows:

- Development and testing of material mixing methods
- Development and testing of material installation techniques
- Determination of the time needed to reach full seal saturation
- Determination of gas and water permeability as well as gas entry/break-through pressure at dry and saturated conditions
- Test of pre-selected measuring instruments.

The installation density of the mockup seal element consisting of a 35clay/65sand mixture amounted to 1.94 g/cm^3, right after seal installation. In the dry state a gas permeability of 6.2E-14 m^2 was determined. As can be seen in **Figure 38**, 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 (11 bars) 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 about 37 months, the total pressure at the packer bottom seems to stabilize at a final value of about 2.5 bars, as can be seen in **Figure 38(b)**. This would be very close to the swelling pressures determined on the small laboratory samples (compare Table 1) Thus, it is very likely that the seal function at full saturation will fulfil the requirements given in Table 1.



(a)



(b)

Figure 38: Evolution of total pressure in the mockup: (a) total pressure along the mockup, (b) total pressure at packer bottom

The first water break-through, indicating a situation close to full seal saturation, was observed in September 2007, after about 29 months of testing. The water injection was stopped by reducing the injection pressure to zero on July 6, 2008 after full saturation was reached. At this stage the water inflow and outflow rates had equalized at about 10 ml/day. The swelling pressure was then allowed to stabilize in the whole seal before the pending gas injection tests. The hydraulic data measured at the break-through situation yielded a water permeability value of about 3E-18 m^2, which is in very good agreement with the data determined from the small samples used in the laboratory. The remaining gas injection test was started on 7 January 2009. Actual data show a clear start of the gas entry at a pressure of about 3.5 bars, a value that confirms the values observed on small lab samples before. Both, the water permeability as well as the gas entry pressure measured at full saturation in Mockup2 confirm the expected optimized sealing properties of the 35/65 clay sand mixture. This result confirms that the required seal function was fulfilled in this test and serves to support the in-situ experiments ongoing at the Mont Terri URL.

The long time until water break-through in the Mockup2, however, exceeds the predicted saturation time significantly. Further research is needed to clarify this discrepancy in relation to the predicted 170 day saturation period and to enhance the respective process understanding for further model improvement.

2.4.5 In-situ test programme definition

In accordance with the functional requirements given in Section 2.4.2 the following parameters are being measured during execution of the in-situ experiments:

- gas permeability of the seal in the initial state by injecting nitrogen gas at the bottom,
- amount of the synthetic formation water injected into the testing system including the seal and the surrounding rock with EDZ
- swelling pressure at the seal top during the saturation phase,
- water permeability of the seal at full saturation,
- gas breakthrough pressure and gas permeability after re-saturation in interaction with the surrounding rock.

After termination of the in-situ tests, samples will be taken from the seal and the surrounding rock for post-test analyses with regard to density, porosity, saturation as well as their homogeneity.

2.4.6 Set-up of test facility

A view into the fully instrumented test niche is given in **Figure 39**. The SB experiments are performed in vertical boreholes of 0.31 m diameter drilled to a depth of 3 m into the floor of the test niche of 5 m width, 4 m height and 8 m length (**Figure 40**). Three boreholes are sealed with 35clay/65sand and 50clay/50sand mixtures, and one borehole for comparison with crushed clay pellets only.

Figure 39: View into the fully equipped SB test niche at the Mt. Terri Rock Laboratory

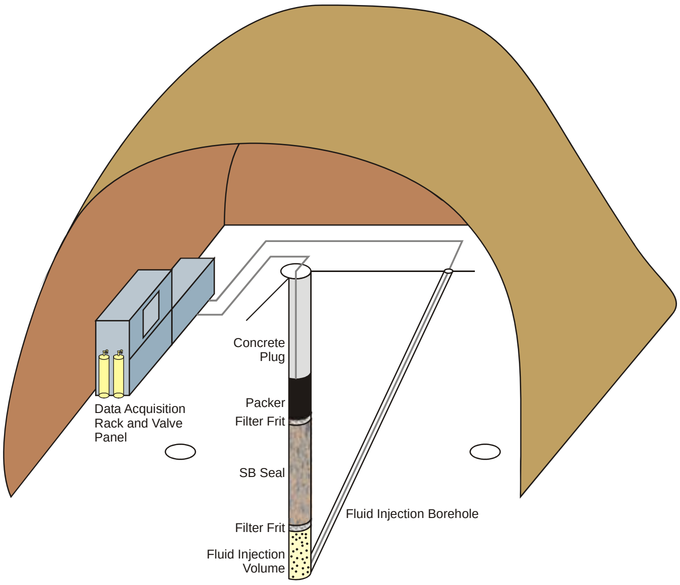


Figure 40: Principle design of a SB- sealing test

All experiments are designed in principle the same way as the mockup experiments. In the lower part of the boreholes (**Figure 40**), the injection volume is filled with gravel as porous medium. At the 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 seal is installed in several layers. Above the seal, a further filter frit is installed for water and gas collection. The entire borehole is sealed against the ambient atmosphere by a gastight packer. At the bottom of the packer, two swelling pressure sensors are installed. *In-situ*, the uppermost part of the test borehole is grouted for keeping the packer in place at the higher swelling pressures developed by the SB seal.

While the water pressure sensors mounted along the tube wall in the mockup 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.

Because of the long saturation times experienced in the mockup tests 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.

For saturation of the seal water 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.

2.4.7 Execution of tests

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. The situation in this test is developing similarly to the mockup. During 38 months of injection (see **Figure 41**), an amount of about 94 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 a loss of water into the surrounding clay rock. The swelling pressure measured at the top of the seal is now more or less stable and amounts at the moment to values between 1.4 and 1.8 bars. This value is in the same order of magnitude as those determined on small laboratory test samples (compare Section 1.5.1, **Figure 9**) and thus, similar sealing properties as those observed on small samples in the laboratory can be expected in this in-situ experiment. At the end of 2008, the swelling pressure seams to start to redistribute. A similar behavior was observed in the Mockup2 shortly before the water breakthrough which is therefore expected to occur in this test within a reasonable period of time.

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 were taken into operation in November 2006. The tests are continuing at more or less unchanged conditions. 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 in the southern part of the test niche showed the expected evolution of swelling pressure in the early saturation phase although the initial injection pressure amounted to only 0.5 bar (**Figure 43** and **Figure 44**). 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 50 and 69 litres of water have been injected into these two test set-ups, respectively.

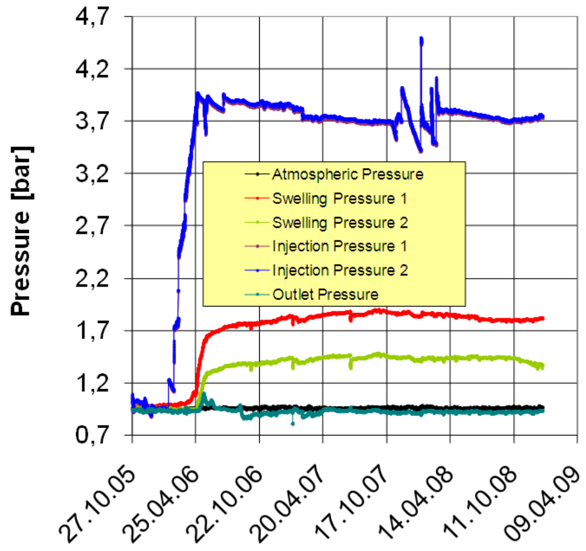


Figure 41: Pressure evolution in test borehole BSB2 sealed with a 35clay/65sand mixture

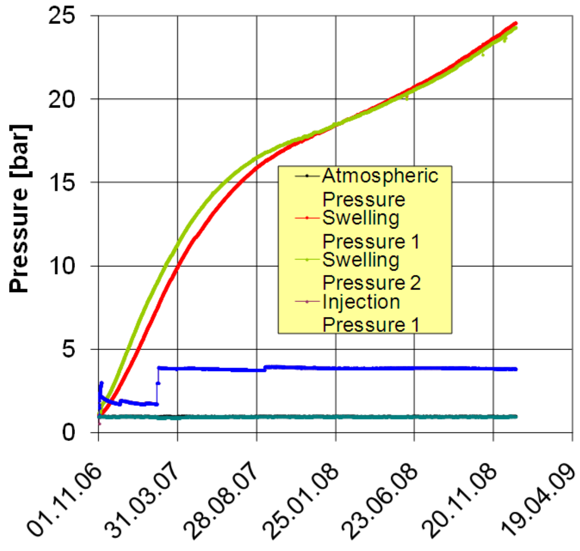


Figure 42: Pressure evolution in test borehole BSB13 sealed with pure bentonite granulate (NAGRA material)

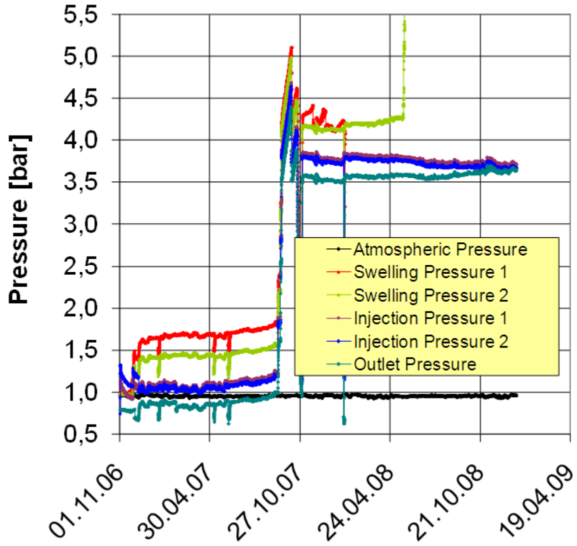


Figure 43: Pressure evolution in test borehole BSB1 sealed with a 35clay/65sand mixture

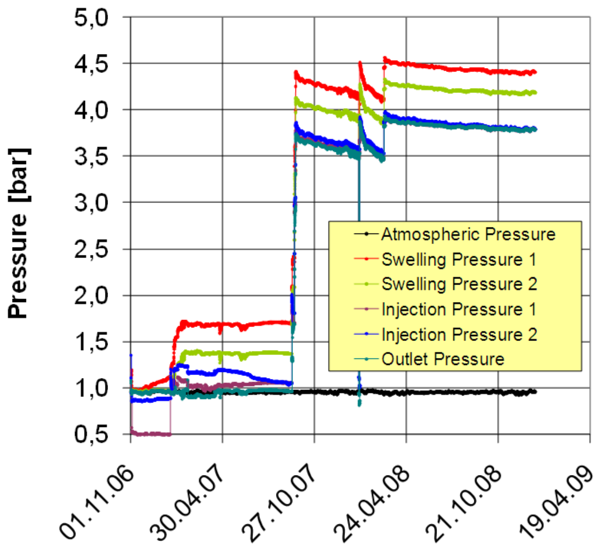


Figure 44: Pressure evolution in test borehole BSB15 sealed with a 50clay/50sand mixture

The test with pure bentonite runs excellently with no disturbances and has meanwhile reached a swelling pressure of almost 24 bars (**Figure 42**). So far, a total amount of 20 litres of water has been injected in this test. The excellent conditions of this test and of the pilot test 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 phases by gas injection tests in all boreholes.

As mentioned above, it is expected that the first water break-through and seal saturation in the in-situ experiments will occur within a reasonable period of time in experiment BSB2 with a 35/65 clay/sand seal. Besides execution of the pending measurements in this test it will have to be decided on basis of actual experimental data how to proceed with the other experiments. So far, discussion with the national funding institution has yielded an elongation of the experiment run time until March 2010.

2.4.8 Post-test activities

According to the expected schedule of the in-situ experiments given in the above section 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 entry/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.

2.4.9 Evaluation of results & summary of conclusions

The results of the SB-experiments obtained so far in the mockup at GRS' laboratory in Braunschweig as well as *in-situ* at the Mont Terri Underground Laboratory 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 mockup 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.

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 9**) 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.

2.5 Seal material installation in annular configuration (by EURIDICE)

2.5.1 Logic of project implementation and planning

See Section 1.6.3.

2.5.2 Input data and functional requirements

A first summary of functional requirements for the sealing material was made as part of Work Package 2. It is given here below in Table 13.

This information was later on complemented by in-situ specific information derived from the performed scoping calculations and laboratory testing (summarized in Sections 2.5.3 and 2.5.4) and the design of the seal support structure (see Section 2.5.6).

Table 13: Functional requirements related to disposal gallery sealing material in the O/N disposal concept

FUNCTIONAL REQUIREMENTS related to the disposal gallery SEALING MATERIAL in the O/N disposal concept		
Description of Objective	**Time Frame of Objective**	**Associated Material Parameters and Criteria**
FUNCTIONS		
The seal should be able to hydraulically compartmentalize the repository sections it is dividing, within a minimum time after installation of the seal.	thermal phase, isolation phase	**Hydraulic conductivity << 10^{-12} m/s** To achieve the objective, the hydraulic conductivity of the material should be sufficiently inferior to the one of the host rock (Boom clay). **Saturation rate > 20 cm/year** (preliminary value) For integration in the PRACLAY experiment, the used material should be able to saturate within a time span of 6 to 12 months. So, since the annular gap is about 20 cm thick, the saturation front should advance at a rate of > 20 cm/year
The gas permeability of the seal should be sufficiently low to force gasses to escape via the host rock instead of via the seal.	thermal phase, isolation phase	The **gas permeability** of the seal should be virtually **zero**
CONSTRAINTS		
The pressure exerted by the seal material may not cause fracturing of the host rock or cause structural instability of gallery wall.	operational phase, thermal phase	**Swelling pressure** after backfill saturation **< 2.2 MPa** (i.e. host rock hydrostatic pressure)
The seal material should not chemically disturb the host rock.	thermal phase, isolation phase	For the host rock, the used material should be relatively chemically similar to Boom clay.
After saturation, the seal should be mechanically self-supporting within the lining of the gallery. Before saturation, the seal should be mechanically (swelling) and chemically (corrosion) compatible with the design of the seal support structures.	thermal phase, isolation phase	No specific mechanical criteria. No problems with corrosion of the seal support structure are anticipated in the time span of the PRACLAY experiment (10 years)
There are no constraints regarding thermal conductivity; the seal is not supposed to act as a thermal shield.	Not applicable	Not applicable

2.5.3 Studies and computer modeling

Table 14 contains several physico-chemical properties of different types of bentonite.

Table 14: Main physico-chemical properties of different bentonites (Tang, 2002 [23])

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 45 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 a swelling potential than the Ca bentonite. However, this difference diminishes with increasing dry density.

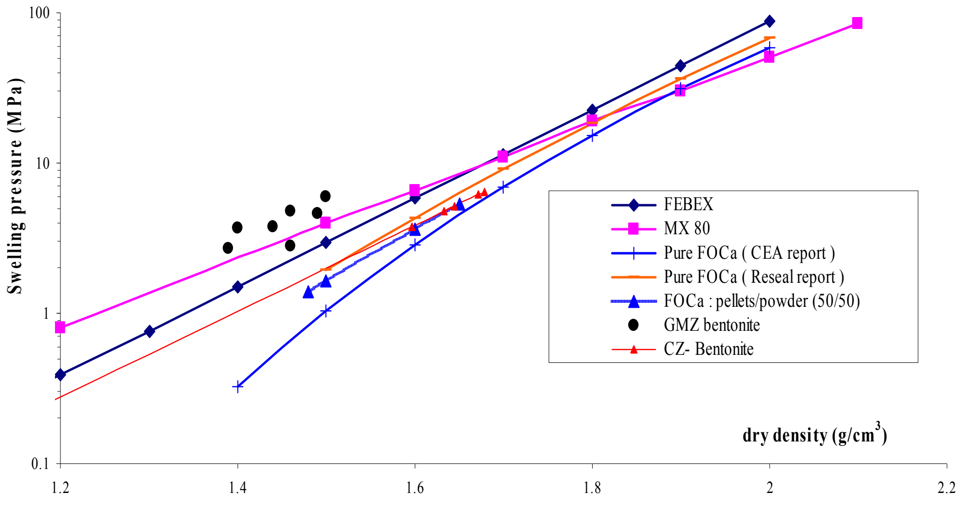


Figure 45: Swelling pressure of different bentonites as a function of the dry density

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 because it has a higher plasticity (see Table 14) and a higher water retention potential than a Ca-rich bentonite like FoCa, as is shown in **Figure 46**.

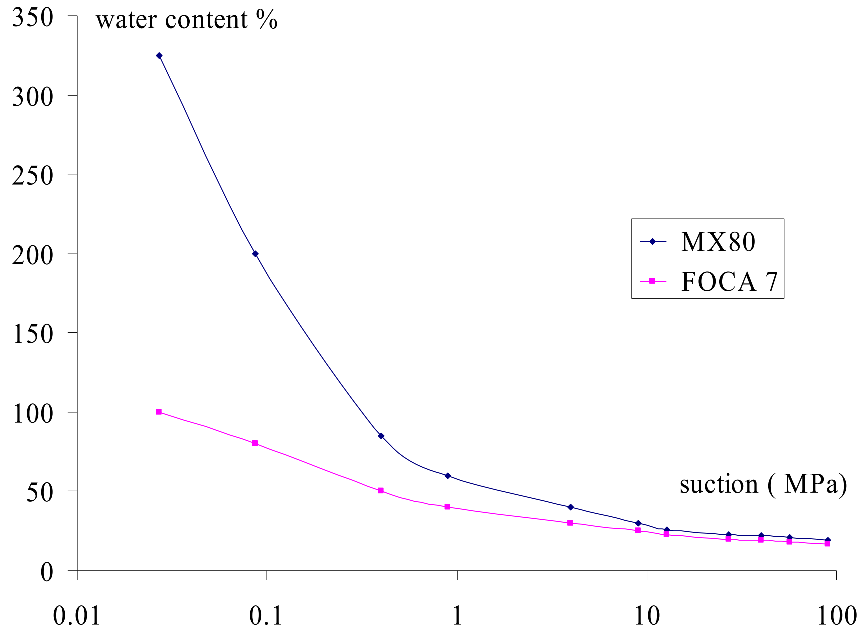


Figure 46: Water retention of MX-80 and FoCa clay (Marcial, 2002 [24])

The initial dry density of the bentonite blocks determines the swelling pressure as well as the final saturated permeability. The technological voids that will be present after the installation are also an important design 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, which is a finite element code developed by Technical University of Catalonia (UPC) and the Centre for Numerical Methods in Engineering (CIMNE). Note that EURIDICE has used version 3.0 of the code.

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.

The numerical scoping calculations provided information on the swelling pressure generation and saturation process of the bentonite seal;

- It was confirmed that the initial dry density and the technological void are the most important parameters controlling the swelling pressure generation. Based on 2D modelling the initial dry density was set at 1.78 t/m^3 and the technological void at 11%.

- 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 will only have 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. A gas build-up test is foreseen to this purpose.

2.5.4 Laboratory testing

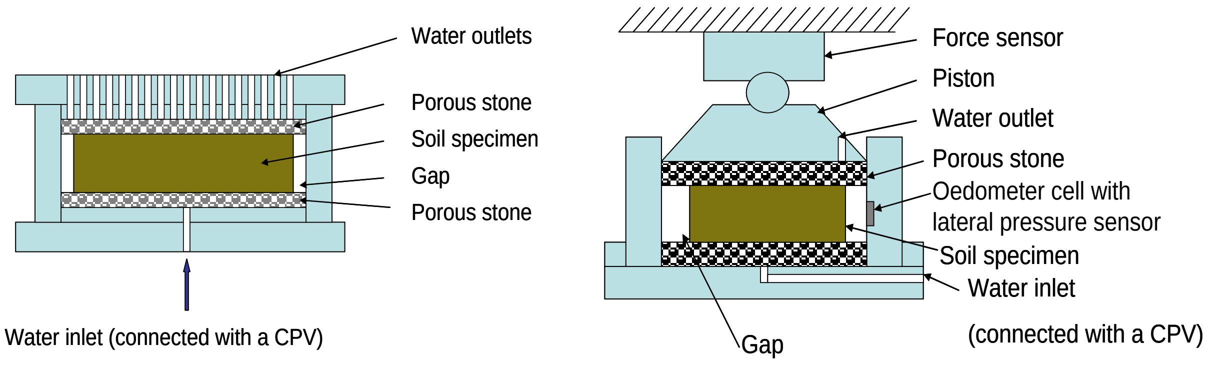
Laboratory test results are important to deduce the THM parameters for numerical scoping calculations, which can provide a guideline for the design of the test, especially for the initial dry density of the bentonite. The initial dry density is a dominant factor to control the swelling pressure and necessary 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 was 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.

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 47(a)**) was a percolation cell of 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 47(b)**) was a constant-volume oedometer of 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).



(a) (b)

Figure 47: Percolation cell (a) and oedometer cell (b)

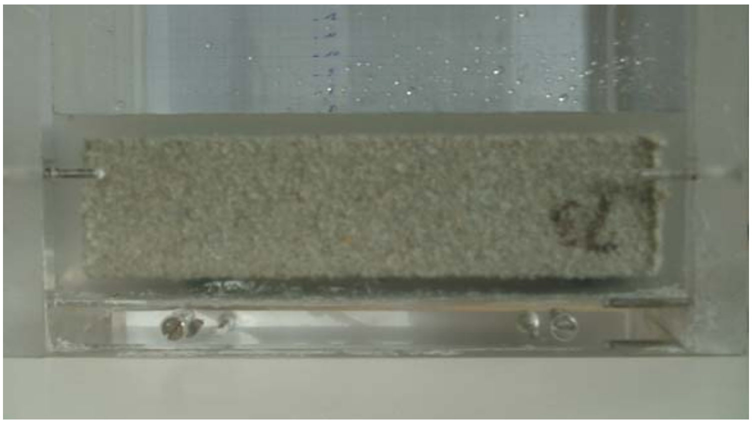
Injection tests were performed in these two different cells in which a cylindrical gap of controlled thickness was prepared between the soil specimen and the cell wall. When starting injection tests, water appeared to flow freely through the gap, keeping the water pressure equal to zero for some time. 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) [25] 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) [26] 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.

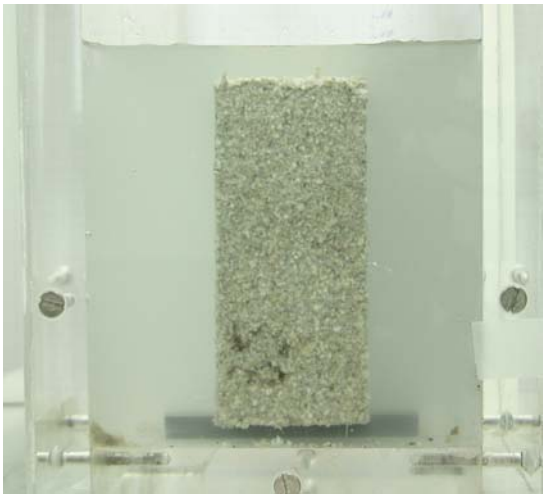
Laboratory tests on bentonite MX-80, to evaluate hydration process on bentonite surfaces

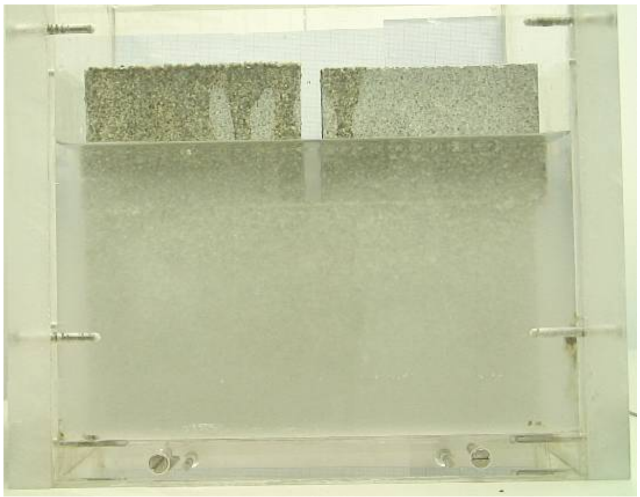
The gaps existing inside the seal present the space allowing the bentonite to swell freely and potentially disintegrate when the artificial injection begins. In order to assess the hydration process on the bentonite surface where gaps are present, a small scale test set-up with a plexi-glass cell was 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 mockup test [27]; the inundation of the mockup after starting 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 mockup. This phenomenon should be avoided in the PRACLAY seal test.



Test 1





Test 2 Test 3

Figure 48: 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 (see **Figure 48**):

- **Test 1**: the bentonite is placed in such way that the compaction plane is horizontal
- **Test 2**: the bentonite is placed in such way that the compaction plane is vertical
- **Test 3**: a joint of 1 cm between two blocks was created to observe the joint behaviour upon hydration.

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.

2.5.5 Test program definition

See Section 1.6.3.

2.5.6 Set-up of the test facility

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 49**). 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 50**.

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 49: Lining in the zone where the hydraulic seal will be placed

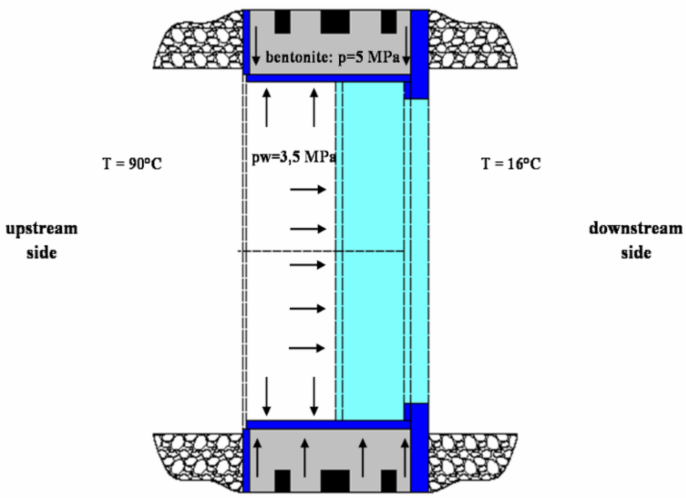


Figure 50: Steel structure: nominal operating conditions and location

2.5.7 Execution of the installation test

The installation of the seal in the underground facility is foreseen for mid-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 20^{th} 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, but this is not part of the contractual scope of ESDRED.

2.5.8 Evaluation of results and summary of conclusions

EURIDICE have prepared the design of the PRACLAY seal steel support structure and have selected MX-80 as the swelling material to be used. The latter selection has involved a literature study, a series of scoping calculations by aid of a computer code and laboratory testing (e.g. at the CERMES institute) focusing on a number of specific aspects related to the interaction 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, the in-situ installation of the PRACLAY seal will fall beyond the contractual end date of ESDRED. The installation is now foreseen for mid-2009. The work by EURIDICE, especially the actual in-situ implementation, will have advanced the phenomenological and technical knowledge base related to the construction of a hydraulic seal in a disposal gallery.

2.6 Micro-seismic non-intrusive monitoring development (by NDA)

2.6.1 Logic of project implementation and planning

See §1.7.3.

2.6.2 Input data and functional requirements

Not applicable; the aim was not to build a mockup or a component based on a specific design.

2.6.3 Studies and computer modeling

In contrast with the other work in Module 1, the computer modeling did not precede the field work. The computer modeling was based on information drawn from the field work.

The computer modeling was considered to be an integral part of the work and is therefore reported under §2.6.7.

2.6.4 Laboratory testing

Not applicable

2.6.5 Test program definition

See §1.7.3

2.6.6 Set-up of the test facility

The HG-A experiment is one of a number that have been undertaken in the Opalinus Clay rocks of the Mont Terri underground rock laboratory (URL) in Switzerland. The HG-A experiment is designed to mimic the evolution of a sealed disposal tunnel, replicating the phases of buffer saturation and gas generation (following corrosion processes of the disposal canister). The aims of the HG-A experiment are to identify gas migration and to measure gas migration through the host rock (the Opalinus Clay geology) and along the engineered seals of a filled tunnel. Investigations in the HG-A experiment focused on a 1m diameter micro-tunnel, which was back-filled with a coarse grained sand mixture (∅ 2 - 6 mm grain size) and closed with a hydraulic mega-packer. Nothing was included in the micro-tunnel to represent the waste form or metallic waste package. Several phases of study were planned representing backfill emplacement, saturation of the micro-tunnel and gas generation.

For the non-intrusive studies, the degree of saturation, gas storage and pressure build-up, and its effects on the geophysical data were monitored over the various phases of the HG-A experiment, using cross-hole seismic tomography. The aim of the experiments was to investigate differences in the seismic data due to variations within the micro-tunnel (both its content and physical condition).

In addition to the boreholes drilled for the experiment, the main components of the set-up are a seismic source (high-frequency sparker), which is inserted into the lower inclined borehole and a 24-channel hydrophone chain (receiver), which is inserted into the upper inclined borehole. To operate these require the boreholes to be filled with liquid (fluid coupled). Therefore, a special purpose sealing cap was required for the upper inclined borehole. The layout of the experimental set-up is shown in **Figure 51**.

A schematic drawing of the experimental setup is shown in **Figure 52**. The Opalinus Clay host rock is known to be highly anisotropic. To a first approximation, the geology of the study area for the HG-A experiment is transversely isotropic about a steeply tilted axis of symmetry, which is illustrated in the (a) part of the Figure.

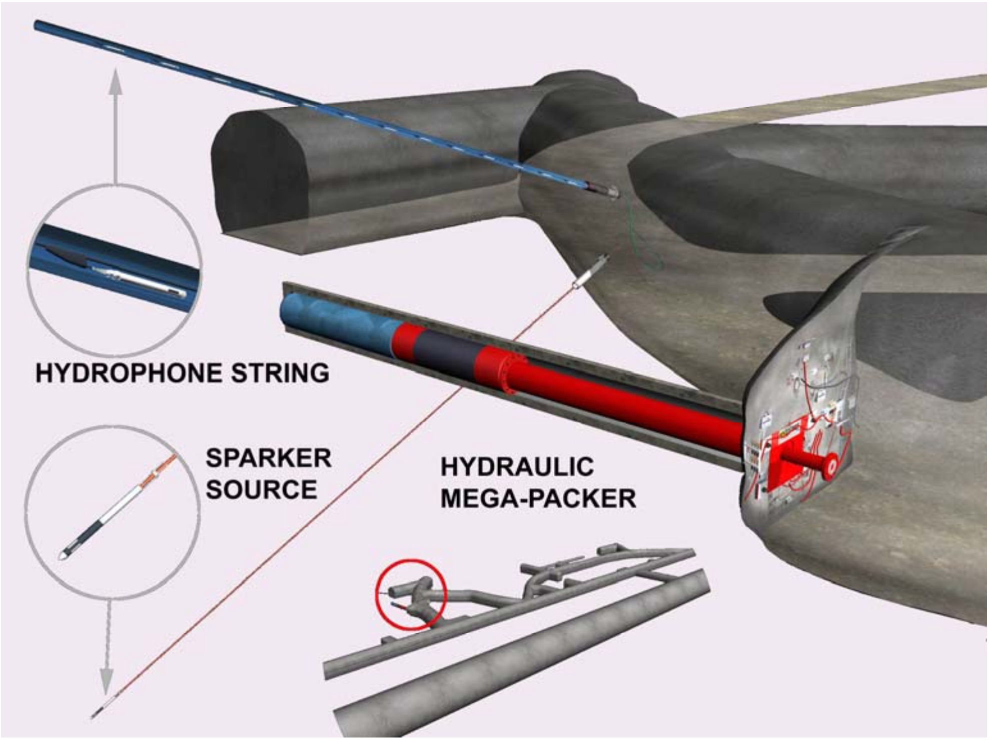


Figure 51: Layout of the HG-A experiment in the Mont Terri URL

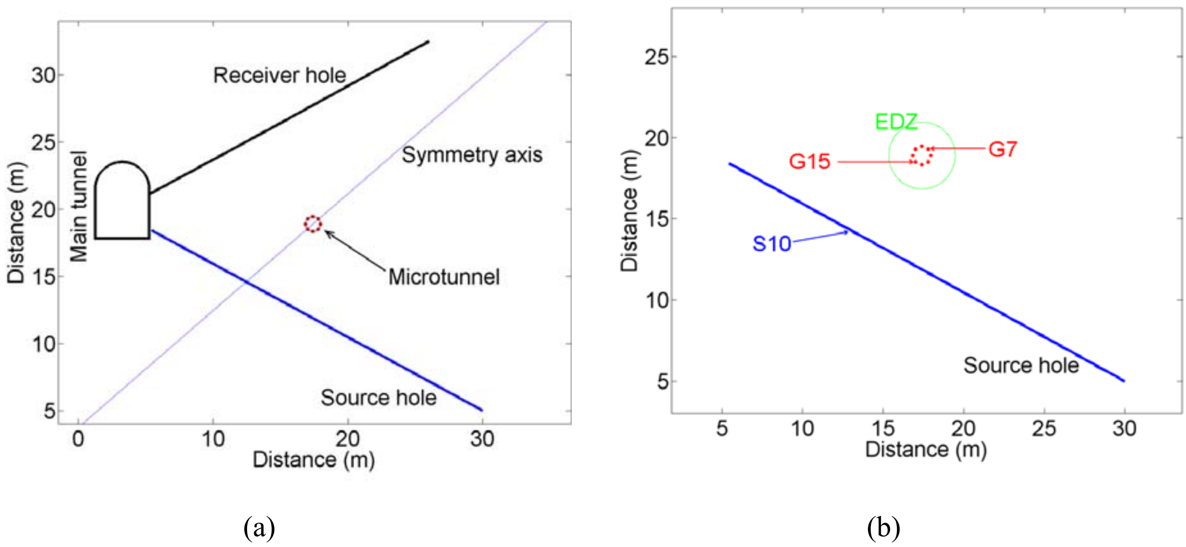


Figure 52: (a) Schematic layout of the non-intrusive seismic tomography experiment at Mont Terri. (b) Experimental setup showing positions of the source at 10 m length along the borehole (S10), geophones G7 and G15 and a sketch of the micro-tunnel EDZ

2.6.7 Execution of the tests

The high frequency P-wave sparker source fired every 0.25 m in the downward-directed borehole was used to generate seismic waves recorded on a 24-channel hydrophone array located in the upward-directed borehole. The hydrophones were spaced at 1 m intervals. By shifting the array three times at intervals of 0.25 m and repeating each shot, a 96-channel hydrophone array with 0.25 m element spacing was synthesized. The energy from each source shot was also recorded on eight vertical-component geophones (natural frequency 100 Hz) distributed around the micro-tunnel wall within the plane of the boreholes.

Repeatability of Measurements

Informative monitoring using seismic tomography requires high levels of quality control. Both the source pulse (including its coupling) and the coupling of the receivers must be consistent throughout all experiments. A consistency check was carried out for the repeatability of signals generated by the source. The results indicated a high level of repeatability for the source signal, when detected by either the hydrophones using a cross-borehole method, or using the geophones in the micro-tunnel as detectors.

A similarly favourable level of reproducibility was observed when experiments using the geophones were repeated at different times (implementing the same set of conditions). However, the reproducibility of data between experiments using the hydrophones was more limited. The signal characteristics arising from two identical experiments carried out differed significantly, probably due to changes in the coupling between the hydrophones and their surroundings. These variable coupling conditions will need to be accounted for during full waveform inversion analysis.

Travel-time Inversion of Cross-hole Hydrophone Data

Tomographic images may be obtained from seismic data through either travel-time inversion (considering only the travel times from the first arriving waves), or full waveform inversion (which takes into account the entire waveform including amplitude and phase). To date, tomographic data have been analysed by travel-time inversion, based on the velocity of seismic wave propagation through the media between the source and the receivers. Development of novel full waveform modelling and inversion schemes to analyse the data obtained is ongoing.

A travel-time inversion of the hydrophone data using the kinematic anisotropic code of Zhou and Greenhalgh (2008) [18] was undertaken for the experiment in which the micro-tunnel was filled with dry sand. For an inversion cell size of 0.60 m, the recovered density-normalized elastic moduli (anisotropic parameters a_{11}, a_{13}, a_{33}, and a_{44} in **Figure 53**) highlight the strongly anisotropic nature of the medium. Note that in that Figure, the black circle identifies the position of the micro-tunnel and the straight black line denotes the axis of symmetry inclined at about 41 degrees to the horizontal. When converted to the Thomsen parameters, these values correspond to ε and δ estimates of up to 0.55 and 0.88, respectively. The inversion results demonstrate that the axis of symmetry is inclined at about 41 degrees to the horizontal. Relatively low seismic velocities are observed ~2 m from the borehole collars (as represented by the very low a_{11}, a_{13}, and a_{44} values at the lower ends of the boreholes in **Figure 53**). This could be the result of excavation damage or desaturation around the gallery 04. The primary features in the tomograms, which are predominantly aligned perpendicular to the symmetry axis, represent layering of the Opalinus Clay.

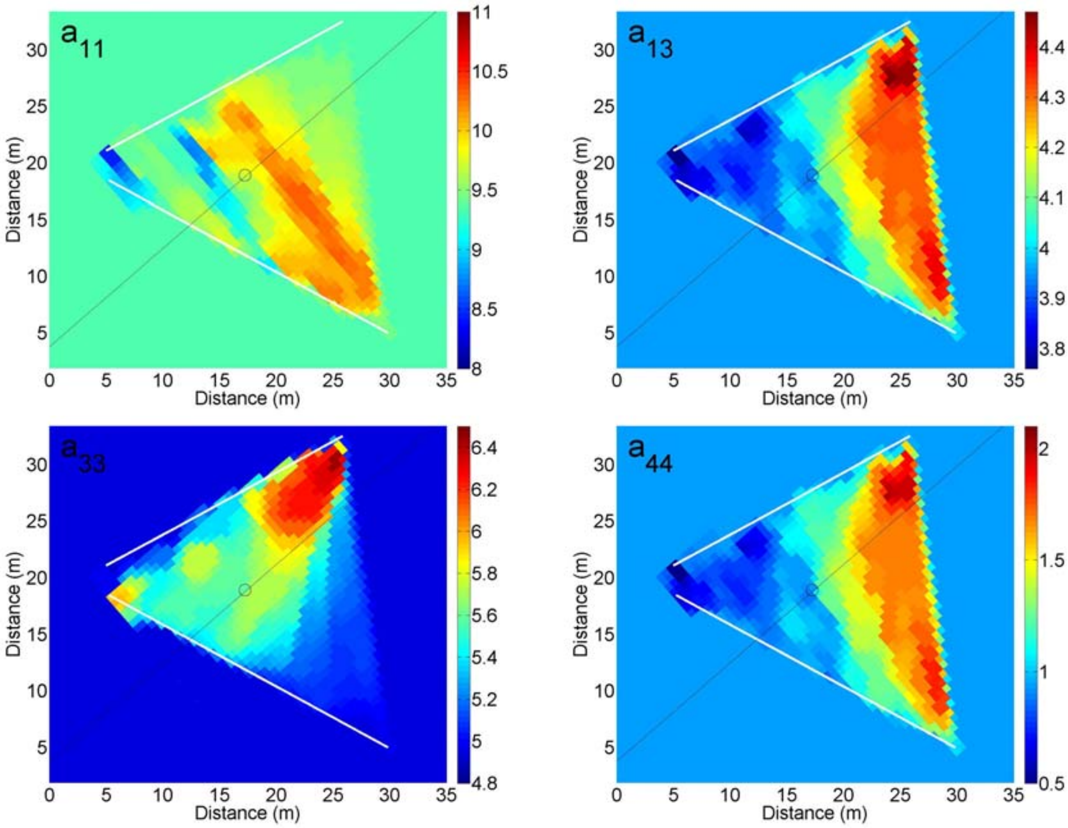


Figure 53: Inverted density-normalized elastic moduli a11, a13, a33, and a44 for a tilted transverse isotropic medium.

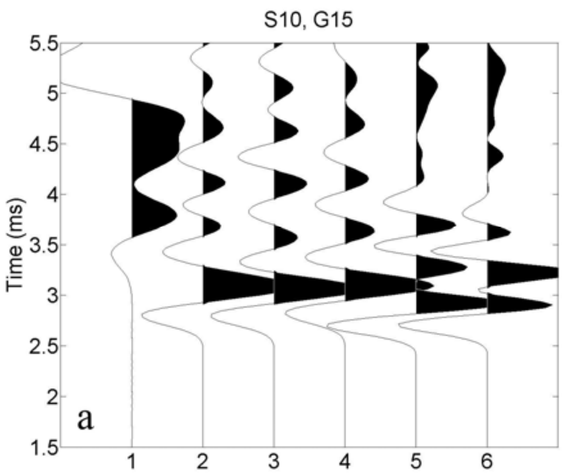
Parameter a_{33} exhibits a pronounced positive anomaly at the upper end of the receiver line. It is supported by elevated values of a_{13} and a_{44} but the origin of this anomaly is unknown. As expected, travel-time inversion is unable to detect the micro-tunnel because of its small diameter. This observation is supported by a travel-time inversion of data from the fully saturated micro-tunnel experiment. The results from this experiment were virtually identical to the tomograms in **Figure 52**.

Travel-time and Waveform Differences in the Micro-tunnel Geophone Data

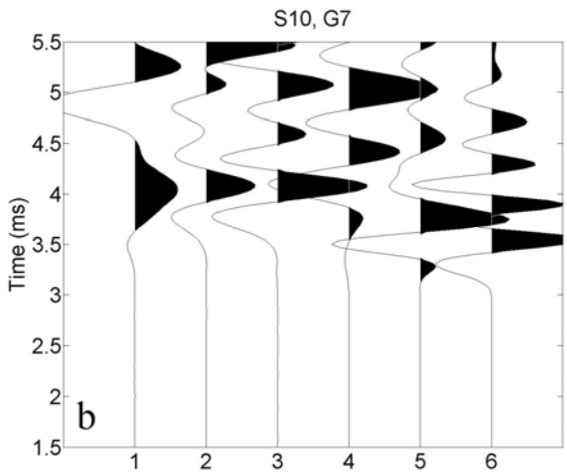
Unlike the cross-hole data collected using hydrophones in an adjacent borehole, recordings from geophones placed directly in the micro-tunnel show significant differences as the experimental conditions are varied. We see variations not only in the travel-times but also in the polarity and character of the first arrivals. For the six different experiments 1 to 6 described in Section 2.6.8, **Figure 54** displays early portions of seismograms from geophones G15 and G7 with the source at the 10 m position S10, as shown in **Figure 54(b)**. Note that he traces recorded during experiments 1 to 6 have been numbered along the x-axis. Since the seismic signal has not traversed the micro-tunnel when it reaches the G15 geophone, differences in the travel-time data at this location can only be attributed to changes in the EDZ of the micro-tunnel.

For experiment 1 (empty micro-tunnel), the geophones were poorly coupled to the micro-tunnel, yielding unreliable seismograms. **Figure 54 (a)** shows that G15 seismograms are very similar for experiments 2, 3, and 4, indicating that the micro-tunnel EDZ is not initially affected by water ingress into the micro-tunnel.

In contrast, the G15 arrival times and waveforms for experiments 5 and 6 are quite different from those of experiments 2, 3, and 4. This variation for the last two experiments may arise because the micro-tunnel has, by this point, been fully saturated for a long time, allowing water to enter the micro-tunnel EDZ. This would lead to resaturation and probable to swelling of the Opalinus Clay (Bossart and Nussbaum, 2006 [20]) and a consequent increase in seismic velocities within the micro-tunnel EDZ.



(a)



(b)

Figure 54: Early arrivals for shot position 10 recorded at geophones: (a) G15, (b) G7

Significant waveform and travel-time changes from experiment to experiment are observable at geophone G7, as shown in **Figure 54(b)**. These variations arise because seismic data collected at G7 is a function of two waves which follow slightly different paths. One wave passes directly through the micro-tunnel and is therefore influenced by the fill material. The other wave is diffracted around the micro-tunnel and is thus influenced primarily by the micro-tunnel EDZ. The first wave to arrive depends on the geophone location in the micro-tunnel, as well as the state of the micro-tunnel and the EDZ. In addition, waves travelling directly through the micro-tunnel strike geophone G7 from below, whereas waves travelling around the micro-tunnel wall strike geophone G7 from above, thus providing the potential for polarity changes and marked amplitude variations that depend upon the arrival times of each wave.

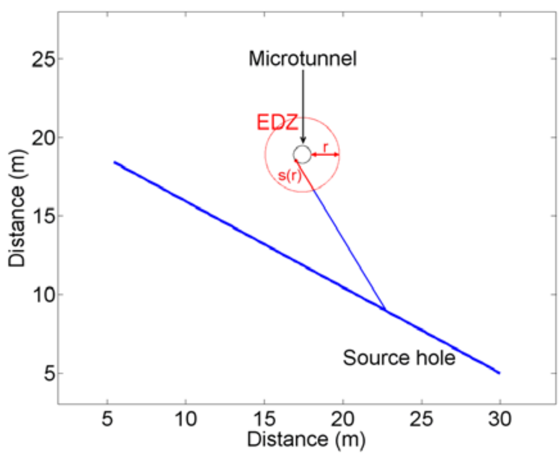
Seismic studies using geophones placed *in-situ* within a micro-tunnel are therefore capable of distinguishing the EDZ of the micro-tunnel from the surrounding environment and distinguishing changes in the conditions in the micro-tunnel as well, both directly and indirectly (through changes in the behaviour of the EDZ).

Attempts have been made to determine information about the micro-tunnel EDZ from the corresponding travel-time data. Assuming a straight ray-path, the travel-time difference Δt of first arrivals between the experiments 2 and 5 can be written as:

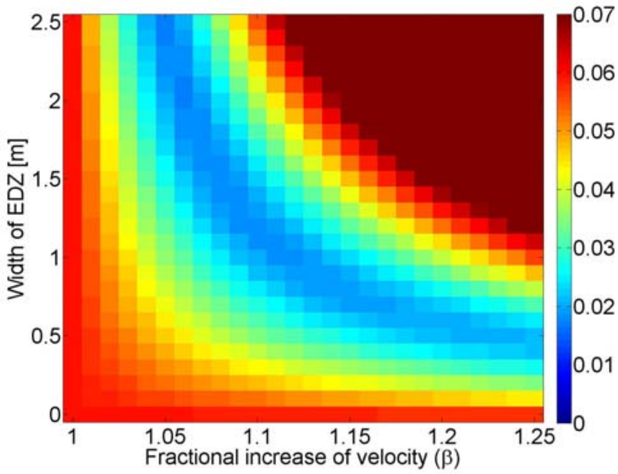
$$\Delta t = s(r)\,(1 - 1 / \beta) / v \qquad (1)$$

where v is the velocity of Opalinus Clay in the micro-tunnel EDZ under dry conditions, β is the fractional increase of velocity in the EDZ caused by the presence of water, r is the width of the EDZ, and $s(r)$ is the length of ray that passes through the EDZ, as illustrated in **Figure 55(a)**. By varying β and r systematically, we attempted to find an optimal combination of the two parameters that explained all observed travel-time differences. As shown in **Figure 55(b)**, there exists a clear trade-off between β and r minimising the misfit, such that *a priori* information on one of the two parameters is required for a unique solution.

The results of seismic investigations on the HG-A experiment at Mont Terri suggest that cross-hole travel-times do not enable information to be gathered about the state of a 1 m diameter micro-tunnel that lies midway between source and receiver boreholes separated by distances of 5-30 m. In contrast, data recorded on geophones mounted within the micro-tunnel provide diagnostic information about the micro-tunnel fill and the state of the micro-tunnel EDZ. Changes in the micro-tunnel fill and EDZ result in marked variations in seismic wave arrival times, polarities and waveforms. A full waveform inversion of the combined geophone and hydrophone data will be undertaken as part of this study to fully assess the imaging capabilities of seismic tomography for this type of application.



(a)



(b)

Figure 55: (a) Straight-ray approximation: First arriving wave propagating from the source to the geophone along an approximately straight line has a lower velocity inside the EDZ (red section of the ray). (b) Root-mean-square errors between observed travel-time differences (experiments 2 and 5) for all source positions, and the predicted differences based on equation (1)

2.6.8 Evaluation of results and summary of conclusions

To date, seismic tomography measurements have been taken on 6 sets of conditions within the micro-tunnel:

1. air-filled,
2. dry sand-filled,
3. 50 % water-saturated sand-filled,
4. nearly fully water-saturated sand-filled,
5. fully water-saturated sand-filled (several months later),
6. fully water-saturated sand-filled and pressurized to 6 bars.

A further four campaigns are planned be undertaken and analysed after the ESDRED Project has finished, these correspond to the gas injection phases.

There are benefits in being able to monitor what is occurring within the EBS, once waste has been isolated, without compromising the integrity of the EBS. Development of non-intrusive monitoring techniques to improve our capability and confidence in these techniques will enable options of more robust and assured monitoring of waste once isolated. The development of practical applications which mimic disposal conditions provide opportunities to test and develop monitoring systems to improve our understanding of the capabilities of these systems particularly to detect relatively small changes over longer timeframes.

A group of partners (NDA, NAGRA, ANDRA) and SOLEXPERTS AG recognised a further opportunity for developing *in-situ* monitoring techniques utilising the construction and testing programme of a low pH shotcrete plug confining a saturated bentonite buffer constructed in granite at the Grimsel Test Site under ESDRED Module 4. The partners initiated Project TEM (Testing and Evaluation of Monitoring Techniques) at Grimsel to provide a unique opportunity for simultaneous comparison of three monitoring methods - wired signal transmission from the EBS, wireless data transmission using magneto-inductive techniques, and observation through non-intrusive cross-hole seismic tomography techniques. This approach provides a means of calibrating and verifying non-intrusive techniques with more researched, better understood techniques and helps to demonstrate their performance and applicability. The novelty of TEM is that the application of each of these techniques is also tested under realistic conditions.

The non-intrusive monitoring development effort, initiated under the EC IP ESDRED programme and continued under Project TEM has applied seismic tomography employing full waveform analysis to improve our understanding of the capability of this technique.

The work undertaken confirms:

- High-resolution seismic measurements for monitoring waste repositories are generally feasible.
- Repeatability of the measurements is most critical for monitoring purposes.
- Geophones installed close to target area proved to be most helpful for identifying temporal changes.
- The equipment employed for this project produced highly repeatable seismic source signatures, but the coupling of the borehole hydrophones turned out to be surprisingly variable.
- The useful bandwidth of the seismic signals extends from up to 4 kHz for the geophones installed in the micro-tunnel and from 1 to 4 kHz for the borehole hydrophones.
- Changing conditions within the HG-A micro-tunnel have minimal effect on the travel times of waves travelling from the source borehole to the receiver borehole. In contrast, effects of changing conditions within the micro-tunnel are very pronounced on recordings from geophones directly installed in the micro-tunnel.

3 SUMMARY AND CONCLUSIONS

3.1 Background and objectives

Important R&D projects, that pre-date ESDRED Module 1, had already studied several bentonite materials and their conditioning, to investigate their application as key materials in buffers, backfills or seals in geological repositories (e.g. RESEAL in Mol, or BOS in Grimsel). Most of these projects had been performed on a small or intermediate scale, and only a few addressed the emplacement techniques related to these components. The demonstration testing, at full scale, that had been performed was basically limited to the vertical disposal configuration (e.g. work by SKB related to the KBS-3V design). From these projects, it was becoming clear that the horizontal configuration would pose specific challenges that had never been sufficiently addressed. At the same time, the horizontal configuration was getting increased consideration in the disposal concepts (reference or alternative) of a number of EU countries. Module 1 was therefore primarily set up to advance the state-of-the-art of the technology related to the construction of the buffer or the backfill around a horizontally disposed high-level waste package.

The work involved the following more specific operational objectives:

- Backfilling of horizontal annular gap:
    - Grout backfilling: to test, first on a 2/3rd scale mockup and then on a 30 m long full scale mockup, whether the annular gap can be filled within a time frame during which the fluidity of the grout can normally be guaranteed (i.e. about 5 hours) and to achieve a quasi complete filling of the void with homogeneous backfill material. The composition of the specific grout is predominantly determined by long-term phenomenological requirements.
    - Dry granular materials: to test on a 2/3rd scale mockup whether the annular gap can be filled, using the dry-gun technique, at a linear pace that would allow application in the actual repository (i.e. faster than one linear m/h) and to achieve a quasi complete filling of the void with homogeneous backfill material. The work involved a pre-selection of the most promising dry granular materials, while focusing on the technological aspects. Robust projection equipment was designed specifically for operating in the disposal gallery under mechanically harsh conditions.
- Prefabricated buffer configuration:
    - The specific objective was to fabricate 10 rings and 2 discs of 2.3 m outer diameter, with 0.8 m diameter inner opening and of 0.5 m thickness. Moreover all of the equipment needed for handling, for assembly in sets of 4, for packaging, for transportation and for storage of the rings once they had been pressed in a mould also needed to be designed, fabricated and tested.
- Granular buffer in combination with prefabricated blocks:
    - The objective was to select and test a number of mixtures of different granule size of MX-80 bentonite derived by computer modeling, to fabricate these mixtures and to use these to perform backfill testing on a 2/3rd scale mockup using auger emplacement technology, with the operational target of obtaining a dry density of 1500 kg/m3.

The general objective related to the low pressure gas entry/break-through seal testing was to check whether the borehole seals would behave as predicted from laboratory experiments. The operational objective was to see whether the entry/break-through pressure during gas injection would be below 2 MPa (a Mont Terri specific value).

Both the seal installation testing (PRACLAY) and the non-intrusive monitoring development had the general objective to advance the associated state-of-the art technological know-how. Specific operational targets were less relevant.

3.2 Implementation and main achievements

In general, the work within ESDRED Module 1 passed through the following sequence: (1) definition of requirements and gathering of input data, (2) computer modelling and/or laboratory testing, (3) mockup or in-situ testing.

The work within Module 1 was subdivided into 6 Work Packages, of which a chronological overview is depicted in **Figure 56**. Note that the shaded bars represent associated additional work that is however outside of ESDRED.

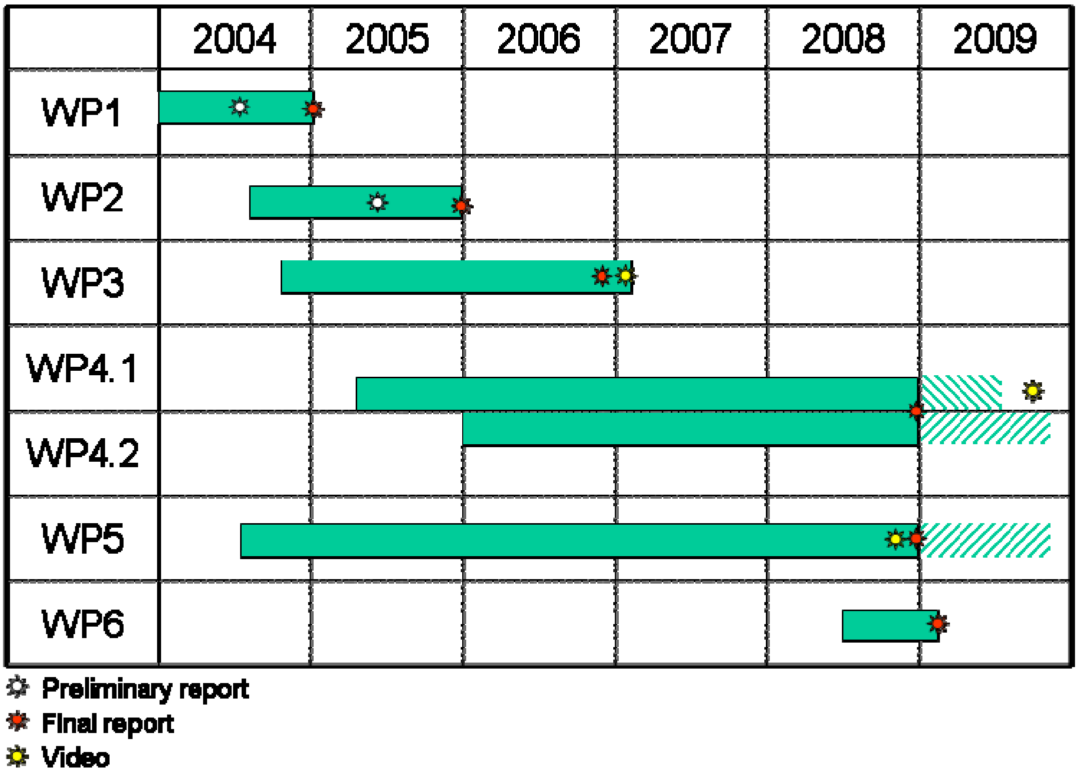


Figure 56: Chronological overview of the execution of the Module 1 Work Packages

Work Package 1 was devoted to the gathering of input data and the definition of functional requirements. Work Package 2 focused on computer simulations, laboratory testing of materials and the design of the test configurations. In Work Package 3, the in-workshop test configurations were constructed and the tests were executed. In Work Package 4, the in-situ testing was performed (4.1 in Mol and 4.2 in Mont Terri), with the exception of the full-scale grout backfill test by O/N, which was performed on a surface mockup. Work Package 5 grouped all the work on non-intrusive monitoring. Work Package 6 was devoted to the Module 1 end-of-project-reporting.

The main achievements, per partner are:

- ANDRA has succeeded in the cold compaction of a MX-80 bentonite / quartz sand mixture prepared as a powder, to obtain the prefabricated buffer rings described in their *Dossier 2005* report to the French Government. ANDRA has also successfully tested the handling of these buffer rings and their rigidity.
- ONDRAF/NIRAS has demonstrated the feasibility of two different emplacement techniques for backfilling the annular void around a horizontally disposed high level waste package: (1) projection of a dry granular material, for which sand, cement, bentonite and mixtures thereof were used, (2) injection of a custom made high pH grout designed to have the required thermal, chemical and physical characteristics. Both emplacement techniques have been tested successfully on 2/3rd-scale mockups. The grout injection technique was also tested on a full scale mockup of 30 m in length. Again, the feasibility of the injection technique was demonstrated, but it was also concluded that the W/C ratio of the specific grout will need to be reduced in the next phases of the development process, to ensure that the grout becomes hard shortly after injection. In general, the backfill tests within ESDRED have provided a broad knowledge basis for this further development process.
- NAGRA, using auger technology and a reduced-scale steel model of a horizontal disposal drift with a waste container disposed on a cradle of prefabricated bentonite blocks, has tested the emplacement of a range of bimodal mixtures of granular bentonite. NAGRA succeeded in achieving the desired dry density of the emplaced buffer material.
- GRS has been (and continues) running performance tests on four seals of different clay/sand composition in boreholes at the Mont Terri URL since October 2005. The results so far of these in-situ tests, and also the results obtained from the preceding (and still ongoing) laboratory mockup tests, confirm the advantageous sealing properties of moderately compacted clay/sand mixtures. Such advantageous sealing properties were previously determined on small samples under ideal conditions in the laboratory. However the seal saturation rates (in the mockup and in-situ) are much slower than predicted by computer models based on earlier work. Hence the in-situ gas entry/break-through injection tests will now most probably be executed around mid-2009. Since the beginning of ESDRED it has always been recognized that the duration of the in-situ tests could easily extend beyond the contractual end date of the Project. The work already completed and the results obtained have considerably advanced the knowledge base regarding moderately compacted bentonite/sand seals in clay host rocks.
- NDA has been successfully conducting a development program to advance the knowledge regarding non-intrusive monitoring based on seismic tomography. A series of measurement campaigns performed around the HG-A tunnel in the Mont Terri URL have been performed. To interpret the information provided by the seismic echoes, an anisotropic model of the clay test environment has been developed and an associated full wave inversion code is being developed, in cooperation with the Swiss Federal Institute of Technology (ETH Zurich) as a part of an ongoing PhD programme. Due to a rescheduling of the HG-A experiment, the last campaign is now anticipated to take place in mid-2009. The performance of this final testing, and the finalization of the wave inversion code, will contribute to the already gathered knowledge base.
- EURIDICE have prepared the design of the PRACLAY seal steel support structure and have selected MX-80 as the swelling material to be used. The latter selection has involved a literature study, a series of scoping calculations by aid of a computer code and laboratory testing (e.g. at the CERMES institute) focusing on a number of specific aspects related to the interaction 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 completed. Due to a rescheduling of works, the in-situ installation of the PRACLAY seal will fall beyond the contractual end date of ESDRED. The installation is now foreseen for the second quarter of 2009. The work by EURIDICE, especially the actual in-situ implementation, will have advanced the phenomenological and technical knowledge base related to the construction of a hydraulic seal in a disposal gallery.

To summarize: at the end of the contractual project time frame, ESDRED Module 1 has achieved all of its objectives. There is one experiment (PRACLAY seal) that is awaiting mid-2009 for work to be finalized and there are two experiments (SB seals and non-intrusive monitoring) that can expect an interesting contribution from additional work that will be performed in 2009 independent of the ESDRED Project. Results on non-intrusive monitoring will be fully reported as part of the MoDeRn Project while the SB experiment will generate a stand alone public document.

3.3 Conclusions and lessons learned

Regarding the construction of the buffer/backfill around emplaced HLW canisters, ESDRED developed a number of off-the-shelf solutions up to a certain level of completeness. These solutions or certain technological aspects thereof, are ready to be shared among partner countries whenever the need might arise.

Regarding the construction of seals in a clay-based repository, the phenomenological and technological knowledge base has been advanced by virtue of two different experiments (SB and PRACLAY seal) conducted as part of ESDRED. This knowledge base will continue to expand in the future as these experiments will be carried on beyond ESDRED. The contribution by ESDRED is however only a first step forward and many more steps will have to be taken in the development of repository sealing techniques.

Regarding non-intrusive monitoring, seismic tomography and the analysis of the data produced by ESDRED has been developed up to a certain level as a useful technique that can be shared among partner countries. So far, the development has focused on applications in a clay repository, but the technology is expandable to other host rocks.

In the course of the project, the partners within Module 1 have developed a better understanding of each other's solutions and the technical challenges involved. This in turn has lead to a better self critical analysis and understanding of each organisation's own solutions. Most of all however, five years of collaboration have led to the formation of a network for cooperation between technological experts within the partner organisations. This has generated collaborative spin-off projects, of which the non-intrusive monitoring experiment at Grimsel URL (TEM Project) is a good example. It has also provided the foundation for cross-organizational initiatives, of which some have been accepted for the 7th EC Framework Program, such as the MoDeRn Project on monitoring. It is this kind of collaboration, more than anything else, which contributes significantly to European integration. To have achieved this is a credit to the ESDRED Project and certainly also to the work in within Module 1.

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APPENDIX 1 : LIST OF PEOPLE WHO PARTICIPATED IN MODULE 1

The following were the ESDRED partner organizations within Module 1:

1. **ONDRAF/NIRAS** (the Belgian waste management organization), fulfilling the role of Module Leader
2. **ANDRA** (the French waste management organization)
3. **NAGRA** (the Swiss waste management organization)
4. **GRS** (German nuclear expert organization)
5. **EURIDICE** (Economic Interest Group created by ONDRAF/NIRAS and the Belgian nuclear research institute SCK.CEN)
6. **NDA** (the British Nuclear Decommissioning Authority)

Note that ENRESA (the Spanish waste management organization) was originally included in Module 1, but stepped out in the course of the Work Package 1. Also note that NDA has replaced NIREX since 2007, as part of the general take-over of activities by the former.

The main subcontractors or supporting organizations in Module 1 were:

- For the backfilling of an annular gap (by ONDRAF/NIRAS):
  - Grout backfill material: **BASF** (after taking over DEGUSSA)
  - Mockup construction and backfilling: **SMET-TUNNELLING**
  - Dry granular materials vehicle design and assembly: **SCK.CEN**, **BAUDOUIN**
- For the prefabrication of bentonite rings (by ANDRA): a consortium called **GME**, which included:
  - Laboratory testing: **CEA**
  - Mould: **SEGULA**, **Clay Technology**, **Ferry Capitain**, **Creusot Mécanique**
- For emplacement of granular buffer in annular configuration (by NAGRA):
  - Computer modeling: **ITASCA**
  - Laboratory testing: **ETH Zürich**, **Clay Technology**
- For the clay/sand seal performance testing (SB experiment, by GRS): no main subcontractors
- For the seal material installation testing (by EURIDICE):
  - Laboratory testing: **CERMES**
  - Seal steel support structure design and installation: **SMET-TUNNELLING**
  - Bentonite provider: **MPC**
- For the non-intrusive monitoring testing (by NDA):
  - Computer modeling: **ETH Zürich**

The following persons played a representative role for the partners in Module 1:

Organization	**Name**	**First Name**
ONDRAF/NIRAS	BEL	Johan
ONDRAF/NIRAS	DE BOCK	Chris
ANDRA	LONDE	Louis
ANDRA	BOSGIRAUD	Jean-Michel
ANDRA	SEIDLER	Wolf
NAGRA	BLUEMLING	Peter
NAGRA	WEBER	Hanspeter
NAGRA	FRIES	Thomas
GRS	ROTHFUCHS	Tilmann
EURIDICE	BERNIER	Frédéric
EURIDICE	VERSTRICHT	Jan
NDA	BREEN	Brendan
NDA	JOHNSON	Mark
ENRESA	*HUERTAS*	*Fernando*

Note: the role of Module 1 Leader was fulfilled by Chris De Bock (ONDRAF/NIRAS)

APPENDIX 2 : LIST OF MODULE 1 DELIVERABLES AND DISSEMINATION LEVEL

Reference	Title	Date	Dissemination Level
Mod1-WP1-D1	Input Data and Functional Requirements	December 23rd 2004	RE
Mod1-WP2-D2.1	Basic Design of Several Buffer Configuration (Preliminary)	August 24th 2005	RE
Mod1-WP2-D2.2	Basic Design of Several Buffer Configuration (Final)	January 11th 2006	RE
Mod1-WP3-D3	In-Workshop Demonstration of Buffer Prefabrication / Installation	February 28th 2007	RE
Mod1-WP4-D4	Report on In-Situ Test Configurations	December 18th 2008	PU
Mod1-WP5-D5	Testing Non-Intrusive Monitoring Systems	December 12th 2008	PU
Mod1-WP6-D6	Evaluation and Final Report	Date of this Report	PU

Dissemination Level:
PU: Public
RE: Restricted
CO: Confidential

APPENDIX 3 : LIST OF ALL ESDRED FINAL REPORTS

Reference	Title	Dissemination Level
Mod1-WP6-D6	Module 1 (Buffer Construction Technology) Final Report	PU
Mod2-WP7-D8	Module 2 (Waste Canister Transfer & Emplacement Technology) Evaluation and Final Report	PU
Mod3-WP5-D6	Module 3 (Heavy Load Emplacement Technology) Evaluation and Final Report	PU
Mod4-WP4-D9	Module 4 (Temporary Sealing Technology) Evaluation and Final Report	PU
Mod5-WP5-D11	Final Report on Communication Actions	PU
Mod5-WP9-D12	Leaflet on ESDRED Results	PU
Mod6-WP4-D6	Final Summary Report	PU

Dissemination Level:
PU: Public
RE: Restricted
CO: Confidential

APPENDIX 4 : LIST OF ACRONYMS

ACRONYM	EXPLANATION
AE	Acoustic Emission monitoring
BET	Brunauer-Emmett-Teller (method for material specific surface area measurement)
C	Waste Canister Containing High Level Vitrified Waste
CU	Spent Fuel Canister (ANDRA)
CU1	SF Waste Canister Containing 4 Spent Fuel Rods (ANDRA)
CU2	SF Waste Canister Containing 1 Spent Fuel Rod (ANDRA)
EB	"Engineered Barrier" (project at Mont Terri)
EBS	Engineered Barrier System
EC	European Commission
EDZ	Excavation Damaged Zone
ERI	Electric Resistance/impedance Imaging (a.k.a. geo-electric)
ESDRED	Engineering Studies and Demonstration of Repository Designs
ETH	Eidgenössische Technische Hochschule (Zürich Technical University)
EU	European Union
FEBEX	"Full-scale HLW Engineered Barriers Experiment" (project at Grimsel)
GPR	Ground-Penetrating Radar
HLW	High Level Waste
ID	Inside Diameter
ILW	Intermediate Level Waste
IP(C)	Integrated Project (Coordinator)
KBS-3H	SKB/POSIVA Horizontal Disposal Concept (reference concept in ESDRED)
KBS-3V	SKB/POSIVA Vertical Disposal Concept (national reference concept)
meq	Milliequivalent (used to express the cation balance per 100 g of dry matter)
MIP	Mercury Intrusion Porosimetry
MOX	Mixed Oxide nuclear fuel (uranium mixed with plutonium)
MS	Microseismic monitoring
MTRL	Mont Terri Rock Laboratory
NEA	Nuclear Energy Agency
O/N	ONDRAF/NIRAS
OD	Outside Diameter
OPC	Ordinary Portland Cement
pH	Unit of measure for acidity and alkalinity of a material
PVC	Polyvinyl Chloride
SB	Project SB (Self-sealing Clay/Sand-Barriers) at Mont Terri
SF	Spent Fuel
TBM	Tunnel Boring Machine
TDR	Time-Domain Reflectometry
TEM	"Testing and Evaluation of Monitoring Techniques" (project at Grimsel)
THM	Thermo-Hydro-Mechanical
TTE	Through-the-earth (monitoring techniques)
UCS	Unconfined Compressive Strength
URL	Underground Research Laboratory
W/C	Water over Cement Ratio
wt%	Percentage based on weight

APPENDIX 5 : COMMON GLOSSARY

WORD	Per IAEA	DEFINITION
ALARA	yes	An optimization process for determining what level of protection and safety makes exposures, and the probability and magnitude of potential exposures, “as low as reasonably achievable, economic and social factors being taken into account”.
Backfill	yes	The material used to refill excavated portions of a repository (drifts, disposal rooms or boreholes) during and after waste has been emplaced
Barrier	yes	A physical obstruction that prevents or delays the movement of radio nuclides or other material between components of a system, for example a waste repository. In general a barrier can be an engineered barrier (see EBS below) or a natural or geological barrier.
Behind		away from the dead end of a disposal cell/drift
Bentonite	yes	A soft light colored clay formed by chemical alteration of volcanic ash. It is composed essentially of montmorillonite and related minerals of the smectite group. Bentonite is used as backfill and buffer material in repositories.
Buffer	yes	Any substance placed around a waste package in a repository to serve as an additional barrier to: stabilize the surrounding environment; restrict the access of groundwater to the waste package; and reduce by sorption the rate of eventual radionuclide migration from the waste
Canister		See « *waste container* »
Cask	yes	A vessel for the transport and/or storage of spent fuel and other radioactive materials. The cask serves several functions. It provides chemical, mechanical, thermal and radiological protection, and dissipates decay heat during handling, transport and storage.
Clay		Within ESDRED this refers to indurated clay in the form of clay stones and argillites. Clays differ greatly mineralogically and chemically but ordinarily their base is hydrous aluminum silicate. NB: “Swelling clays” refers to specific types of clays used in EBS (see “Bentonite”) and in seals.

WORD	Per IAEA	DEFINITION
Conditioning	yes	Those operations that produce a waste package suitable for handling, transport, storage and/or disposal. Conditioning may include the conversion of the waste to a waste form, enclosure of the waste in canisters, and, if necessary, providing an over pack.
Criticality	Per US Nuclear Regulatory Commission	A term used in reactor physics to describe the state when the number of neutrons released by fission is exactly balanced by the neutrons being absorbed (by the fuel and poisons) and escaping the reactor core. A reactor is said to be "critical" when it achieves a self-sustaining nuclear chain reaction, as when the reactor is operating. In waste disposal designs the objective is to keep any fissile material in a sub-critical state so that any heat generated is due to natural decay only.
Decline		An excavation, in rock, for providing access from surface to the underground. Also called a ramp or access ramp. Essentially an inclined tunnel.
Demonstrator		A custom designed prototype piece of equipment built to prove a design concept and to show that it works; hence used to demonstrate.
Disposal	yes	The emplacement of waste in an appropriate facility without the intention of retrieval i.e. permanently.
Disposal Cell		Typically a short tunnel/drift/borehole excavated in an underground repository for the purpose of disposing packages of radioactive waste.
Disposal Drift		Typically a long tunnel/drift excavated in an underground repository for the purpose of disposing packages of radioactive waste
Disposal Package		The final Waste Package which is placed into a repository without further conditioning i.e. the Super-Container, the Primary Package with over pack or the Primary Package without over pack.
Drift		A horizontal or nearly horizontal mined passageway
EBS	yes	Engineered barrier system; the designed or engineered components of a repository including waste packages and other engineered barriers. See also definition of barrier above.
EDZ		Excavation damage zone; used to describe the area surrounding a rock excavation which has been altered by excavation from its initial state usually by the formation of fractures or micro fissures.

WORD	Per IAEA	DEFINITION
ESDRED Concept		This is a variation of the reference National Concept which is used within the ESDRED Project. Example: Sweden's national concept is "Vertical" however SKB's concept within ESDRED is horizontal
Front, in front of		towards the dead end of a disposal cell/drift
Functional Requirements		Generally refers to expected functions and associated levels of performance that must be met by one or several design elements. Within ESDRED, similar to flexible design criteria or flexible input data; generally refers to criteria or elements that are open to discussion and/or negotiation
Gate		A type of radiation protection door installed on a cask as well as on the head of a disposal cell.
Hoist		A machine, driven by an electric motor, used to raise or lower a conveyance in a shaft.
HRL		Like a URL (see below) but located in hard crystalline rock.
Implementer		The private corporation or public body responsible for constructing and operating a repository.
Input Data		Within ESDRED, similar to fixed design criteria; generally refers to criteria or elements that are unavoidable and not open to discussion and/or negotiation
Long Term		Generally intended to mean extending in time beyond the final closure of a repository
Matrix		A non-radioactive material used to immobilize waste. Examples of matrices are bitumen, cement, various polymers and glass
Matrix diffusion		Diffusion of solutes from a water-bearing fracture to pores and microfractures of the adjacent rock matrix and vice versa
Overpack	yes	A secondary (or additional) outer container for one or more waste packages, used for handling, transport, storage or disposal.
Plug		Sometimes used interchangeably with SEAL but not within ESDRED where it refers to a concrete mass that serves as a backstop or abutment to resist the pressures eventually exerted on a seal by the swelling buffers.
Primary Package		A package of radioactive material as delivered by the producer; before conditioning, for disposal
Ramp		See decline.

WORD	Per IAEA	DEFINITION
Repository		A nuclear facility where waste is emplaced for disposal
Repository system		The combination of the repository and the host rock
Retrievability (EUR 19145)		The ability provided by the repository system, to retrieve waste packages for whatever reason retrieval might be wanted for.
Reversibility		Implies a step wise disposal process and in particular refers to the ability of a repository system, for whatever reason, to reverse the steps that have been executed so far in its development.
Safety Case	yes	An integrated collection of arguments and evidence to demonstrate the safety of a facility. This will normally also include a safety assessment.
Salt		One of the 3 main host rocks being considered worldwide for the disposal of highly active waste materials.
Seal	yes	Engineered barriers placed in passages within and leading to a repository to isolate the waste and to prevent seepage leakage of water into or radionuclide migration from the repository area. Sealing is performed as part of repository closure process.
Shaft		A vertical access way, excavated in overburden (if any) and bedrock, used to connect the surface with one or more horizons underground. Typically outfitted with one or more hoist and one or more conveyances unless used exclusively for ventilation in which case it may be left bald.
Shielding	yes	A material interposed between a source of radiation and persons, or equipment or other objects, in order to absorb radiation and thereby reduce radiation exposure.
Shotcrete		Mortar or concrete pneumatically projected onto a surface at high velocity.
Spent Fuel	yes	Nuclear fuel removed from a reactor following irradiation, which is no longer usable in its present form because of depletion of fissile material & build up of poison or radiation damage.
Storage	yes	The holding of spent fuel of radioactive waste in a facility that provides for its containment, with the intention of retrieval. Storage is by definition an interim measure.
Super Container		Generally seen as a disposal package that, unlike other disposal packages also incorporates bentonitic or cementitious buffer material.

WORD	Per IAEA	DEFINITION
Transmutation	yes	The conversion of one element into another. Transmutation is under study as a means of converting longer lived radionuclides into shorter lived or stable radionuclides.
Transuranic Waste		Alpha bearing waste that consists of material contaminated with elements that have atomic numbers greater than that of uranium (92), the heaviest natural element.
URL	yes	Underground Research Laboratory constructed for the purpose of conducting in-situ testing. The objective is to conduct tests in a geological environment that is essentially equivalent to the environment of a potential repository.
Waste		Material in gaseous, liquid or solid form for which no further use is foreseen
Waste Container	yes	The vessel into which the waste form is placed for handling, transport, storage and/or eventual disposal; also the outer barrier protecting the waste from external intrusions. The waste container is a component of the waste package. For example, the "canister" into which molten HLW glass would be poured.
Waste form		Waste in its physical and chemical form after treatment and/or conditioning (resulting in a solid product) prior to packaging. The waste form is a component of the waste package
Waste Package	yes	The product of conditioning that includes the waste form and any container(s) and internal barriers (e.g. absorbing materials and Liners), prepared in accordance with the requirements for handling, transport, storage and/or disposal.
Wireless Monitoring		System for monitoring phenomenology in front of a seal or plug without installing cables or wires through any of the barriers intended to isolate one or more disposal packages