Sealing experiments at the Tournemire URL

The SEALEX Project

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Abstract
In 2015, IRSN will be in charge of reviewing Andra's application for construction of a geological disposal. In order to support its safety assessment of this future "dossier" and to develop the required technical appraisal for assessing design that will be presented by the implementer to seal the disposal, IRSN has undertaken the SEALEX research project. This project aims at identifying conditions (technical specifications, design, construction, defects…) that will control the performance of swelling clay-based sealing systems at long-term. This paper presents the main objectives of this in situ experiments programme, details the choices that were made during its design phase, and describes the in situ experiments set-up that will be emplaced from 2010 in the Tournemire Underground Research Laboratory.

1 CONTEXT AND OBJECTIVES

1.1 Specific issues related to the safety of geological disposals

From the feedback of the safety assessment IRSN carried out on Andra's Dossier 2005 [1], several key safety issues related to geological disposal of IL-HLW were identified among which: i) The main perturbations and their influence on the confinement properties of the disposal components; ii) Technical feasibility of the seals with respect to their safety functions and their expected performance level. It was recognised that these issues still need to be evaluated via in situ experiments performed at representative scale, especially focused on quantifying the long-term hydraulic performance.

1.2 Feedback from previous experiments

From a back analysis of previous in situ sealing experiments (TSX at the AECL, Canada; FEBEX at Grimsel, Switzerland; EB at the Mont Terri, Switzerland; RESEAL at Hades URL, Belgium; KEY at the LSMHM, France), several aspects were identified as remaining challenges:

- The forced resaturation generally leads to heterogeneous saturation fields at short and mid-terms (FEBEX), which can also lead to heterogeneities in the final porosity at saturated state. In addition, depending on the forced resaturation condition, some flow channelling within the clay core can be produced (clay erosion), though this is more specifically related to localised water fluxes in crystalline rocks;
- There are often some losses of injected water either from leakage through the injection/confinement system or from direct intake by the host-rock, which makes it

difficult to quantify accurately the real water intake by the clay core itself (e.g. TSX, EB, KEY);
- The seal evolution upon a confinement failure (failure of the confining plug) was not properly studied in these experiments (though the last phase of FEBEX test partly tackled this point).

1.3 Main objectives of the SEALEX project

Accordingly, as a part of the overall IRSN R&D programme that provides the bases for scientific expertise on disposal safety, the so-called SEALEX project was built with specific focus on sealing systems efficiency (cell seals, gallery seals, shaft seals). Thanks to limited-size in situ experiments[1] focused on performance[2] at long-term (i.e. under isothermal and water-saturated conditions) of sealing systems (clay cores associated with confining plugs), SEALEX is dedicated to:

- Test the long-term hydraulic performance of sealing systems (in normal conditions, i.e. non altered), for different core compositions (pure MX80, sand/MX80 mixtures) and conditionings (pre-compacted blocks or in situ compacted powder);
- Quantify the impact of intra core geometry —construction joints in the case of pre-compacted blocks— on the hydraulic properties of sealing systems;
- Quantify the effect of altered conditions —an incomplete saturation of the swelling clay or an incidental decrease of the swelling pressure caused by a failure of the concrete confining plugs— on its performance, which tests the concept robustness with respect to the hydraulic characteristics of the system.

The SEALEX project does not aim at demonstrating sealing capabilities of a geological disposal, which is the implementer's responsibility. Rather, it is dedicated to test various technical parameters that could influence global hydraulic and mechanical performances of a seal, and to provide IRSN with feedback and knowledge on the key parameters that the implementer should specify and control in situ.

2 DESIGN CHOICES

2.1 Underlying hypotheses

In situ experiments that are foreseen in SEALEX are focused on the hydraulic behaviour at long-term (in the post-closure phase), i.e. after the full resaturation of the seals (especially their bentonite-based cores). From an experimental viewpoint, this restriction was used to neglect the effects of:

- *The gaseous hydrogen component* (steel corrosion, radiolysis), which makes experiments more simple to perform but which relies on the assumption that in fine the H_2 gas did not affect both the material and interface characteristics and also the full resaturation (this issue is actually tackled in an other project);
- *The temperature produced from the heat emitting radioactive waste*. This assumption is supported by previous in situ experiments taking the thermal effect (for temperatures lower than 100°C) into account, and which have shown no strong

[1] Seal experiments at representative scale with respect to disposal cell seals, emplaced at the Tournemire Underground Research Laboratory.
[2] Allow controlling the potential water fluxes.

(irreversible) effects of the temperature on the mechanical (swelling capacity) and hydraulic (conductivity, water retention) behaviour of some bentonite-based core materials (this was shown by measuring properties of bentonite samples after dismantling the FEBEX in situ test and by comparing them with initial ones, see e.g. [2]).

Regarding the influence of the host-rock/bentonite interface, observations made when dismantling the FEBEX in situ test [2] showed that the swelling of the bentonite has induced the filling of all the constructions gaps of the barrier. Besides, lab experiments performed on small mock-ups of bentonite/argillite interface [3] led to water intrinsic permeability of $2 \cdot 10^{-21}$ m^2, i.e. about the same order as the bulk material. Both these results show the sealing efficiency of the bentonite/argillite interface at fully saturated states when gas migration is not considered. Accordingly, the influence of the host-rock/bentonite interface is not specifically investigated in SEALEX.

2.2 Test geometry

2.2.1 Generic layout

The generic layout of the SEALEX in situ experiments consists of several components inserted in a horizontal large diameter borehole excavated in the Tournemire argillite (see Fig.1a). In more details (see Fig.1b): i) The swelling clay core (MX80 bentonite based) is sandwiched between two porous plates (e.g. sintered steel filter or porous ceramic); ii) The upstream plate is in direct contact with host-rock while the downstream one is retained by a confining system (referred to as a confining plug) maintaining a constant volume condition; iii) A temporary venting system enhances air evacuation from the initial macro-voids (radial clearance, axial clearance, etc.) during flooding of the system; iv) Water tightness of the interface between the rock and the confining plug is achieved by a packer like device, which will prevent water leaks during the whole test duration.

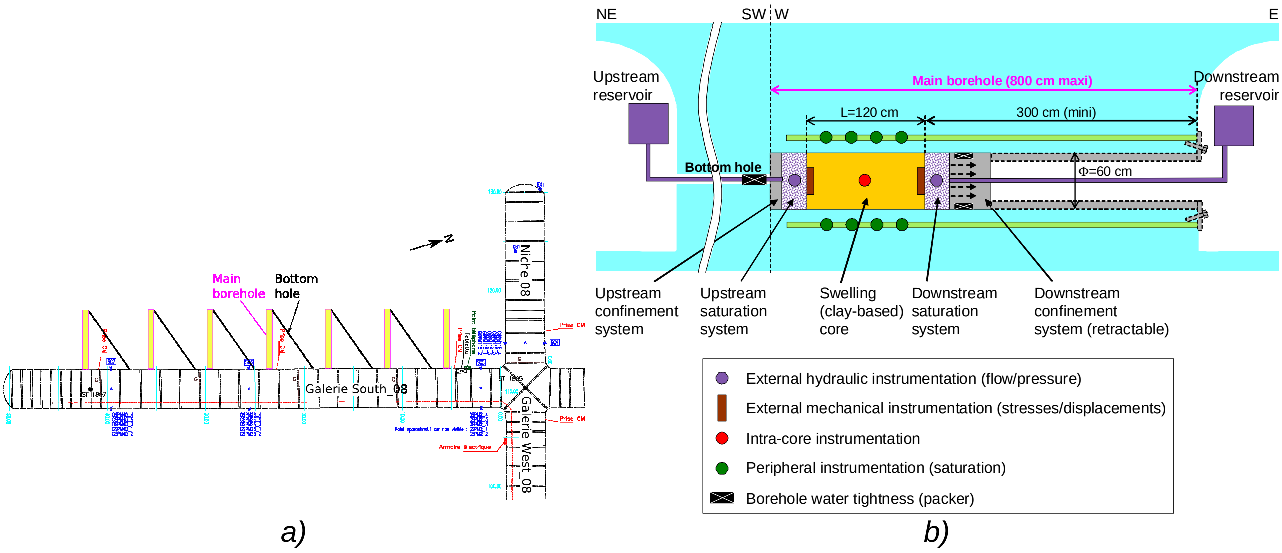


Figure 1: Detail of the SEALEX tests: planned position of the main boreholes and bottom boreholes (dimensions in meters); b) Generic layout (exploded view)

Regarding the test operational phases, water will first be pumped into the injection chambers by means of injection lines connected to the injection chambers, which will slowly saturate the clay core. At a first stage, it will induce a swelling of the clay core, which will close the inner voids of the system (technological voids) and reduce the overall permeability. Then, once the voids will be filled, a swelling pressure will develop due to the constant volume condition, which will further reduce permeability. Continuous monitoring of the flow rate both at injection (upstream) and measurement (downstream) chambers will allow inferring the evolution of the global saturation of the core. After the end of the resaturation phase (which may likely last several years), hydraulic tests will be performed to determine the overall hydraulic properties (permeability, occurrence of leakage) of the corresponding sealing systems.

2.2.2 Dimensions of the clay-based core

In order to define the dimensions of the tests, especially the clay-based core (diameter and length), both scoping calculations of the resaturation kinetics and an analysis of the test objectives were carried out.

Scoping calculations [4], namely two-phases (water-air) flow simulations using TOUGH2 [5] of the core hydration were performed for several core geometries, considering length of either 1.80 m or 1.20 m and diameter of either 60 cm or 40 cm, and considering boundary conditions and loading (i.e. forced saturation at porous plates) consistent with the test layout given in Figure 1b. The influence of geometric details (such as the annulus void between the bentonite core and the argillite) was also studied. Water and air fluxes were computed according to generalized Darcy law, taking into account the dependence of capillary pressure and relative permeabilities (gas and liquid) upon saturation. The impact of specific parameters (the clay core intrinsic permeability, its retention curve and relative permeability law) on the saturation kinetics field was also studied. An analysis of the studied configurations led to the following conclusions:

- In the reference configuration (60 cm diameter, argillite intrinsic water permeability $k_{arg} = 10^{-21}$ m^2, no annular voids), the radial resaturation component is negligible (i.e. radial fluxes are small compared to axial ones). This holds true even under a higher argillite intrinsic water permeability ($k_{arg} = 10^{-20}$ m^2);
- The core length L is an important factor that controls the resaturation profiles, as the core resaturation is mainly controlled by axial water fluxes that originate from the water pressure (100 kPa) imposed at the injection chambers (i.e. an unlimited amount of water is available);
- Quite logically, the first-order dimensioning parameter with respect to the resaturation kinetics is the length L of the clay core, its diameter playing only to the second order;
- The occurrence of an annular void around the clay core (technological voids) can substantially accelerate the resaturation rate, provided these voids are water-filled at initial stages. In this case, they effectively allow an initial faster water flow from the injection chambers towards the core, which then enhances the radial resaturation component (the larger this annular volume, the faster the resaturation).

Dimensions of the SEALEX experiments were derived from the compromise between two partially contradictory needs:

- Firstly, minimizing the resaturation time in order to perform tests in a reasonable schedule (few years). From the scoping calculations, L should then be minimized;
- Secondly, keeping the test dimensions as representative as possible of the disposal concept:
  <u>Regarding the radial dimension:</u> Among the 2 diameters initially foreseen (40 and 60 cm), the largest one (60 cm) remains close enough of the foreseen HA disposal cell diameter (around 70 cm) to ensure a good representativeness along this

direction. Additionally, the smallest diameter has two drawbacks on the swelling pressure obtained at saturation compared to the larger one[3]: i) a larger absolute uncertainty on the final swelling pressure, ii) the need to increase the initial bentonite dry density, which if precompacted blocks are used, leads to technological difficulties (higher compacting energy required). These three arguments all favoured the larger diameter (60 cm), which thus was adopted;

Regarding the axial dimension: In the Andra preliminary concept, the clay core of HA disposal cell seals is 3 m long, this value being justified by the requirement of maintaining a 1 MPa minimal swelling pressure within the core, taking into account the alkaline perturbation extent (0.6 m at 10^5 a, 1.8 m at 10^6 a, see p.198 of [6]). In other words, at long term (10^6 a), the effective swelling core length L is only 1.2 m long. Thus a 1.20 m length was adopted here.

2.3 Specification of the bentonite-based core material properties

Firstly, the nominal swelling pressure P_{sw} of the clay core must be specified, which must fall within the admissible range defined from the following two characteristic values:

- The lower bound P_{sw} required to guarantee that a low permeability of the sealing is obtained at long and very long term, even after failure of the confining plugs. This value derives from a hypothesis of volume expansion of the seal core (thus a decrease of its density). Here we consider the value 1 MPa, corresponding to the choice made in [6] to reach a hydraulic conductivity lower than 10^{-11} m/s;
- The upper bound P_{sw} that must not be exceeded to avoid inducing fracturing at the bentonite/host-rock interface. From theoretical estimations (using in situ stress field and rock properties as input) and in situ measurements based on hydrofracturing tests [7] [8], this value can be estimated around 4 MPa at the Tournemire site.

From this admissible range, a nominal swelling pressure P_{sw} = 3-4 MPa is adopted, which is a value close to the nominal value defined in [6].

Secondly, a clay-based core material must then be specified to obtain this nominal value at fully saturated state. Numerous studies carried out on bentonite-based materials have shown that P_{sw} is strongly correlated to the dry density of the clay fraction (ρ_d), and that this result holds true both for pure bentonite and for bentonite/sand mixtures (see e.g. [9]). As an illustration, a data fit of the results [9] obtained on MX80 (considering both pure and 70/30 mixture of MX80/sand) leads to the relation:

$$P_{sw} = 0.0004 \exp(6.9\rho_d)$$

where ρ_d is the dry density of the montmorillonite within the bulk material. Some other properties of the clay core (intrinsic permeability, compressibility, retention curve...) are also well correlated to the dry density. As an example, a data fit of the intrinsic permeability results [9] leads to the relation:

$$k = 6 \cdot 10^{-15} \exp(-10.3\rho_d)$$

To summarize, the effective dry density of the bentonite fraction is the main parameter that must be specified or adjusted in the SEALEX tests. Given the range $3 < P_{sw} < 4$ MPa, the $P_{sw}(\rho_d)$ relation predicts a corresponding dry density range $1.335 < \rho_d < 1.375$ g/cm^3, which will be verified through laboratory experiments.

[3] In the presence of an initial annular void, the absolute uncertainty on the borehole radius impacts the initial void volume (which, at saturation, will be balanced by the core swelling) more strongly for smaller diameters than for larger ones.

3 DESCRIPTION OF THE SEALEX IN SITU TEST PROGRAMME

All the experiments will be emplaced in the Tournemire Underground Research Laboratory (Toarcian argillite), via horizontal boreholes (diameter 60 cm) excavated from recent drifts (2008). Each experiment (see Figure 1 and Figure 2) represents a generic seal mock-up (i.e. either at a relevant scale with respect to real cell seals, or with relevant characteristics), except the presence of an artificial resaturation system and of some instrumentation.

Regarding the intra-core instrumentation, it was chosen to limit as much as possible the disturbance induced by instrumentation on the core performance, thus to avoid the potential occurrence of flow pathways along signal wire paths (unless only wireless sensors are used). Accordingly, two types of tests have been designed: reference tests and performance tests.

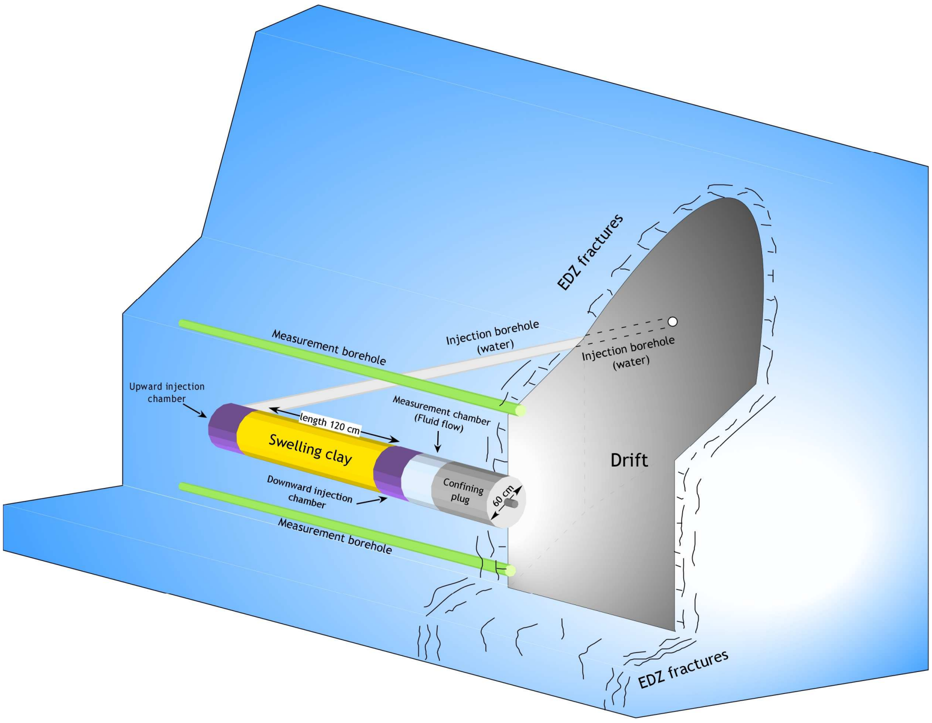


Figure 2. Schematic view of the performance test PT-N1

3.1 Performance tests

Five performance tests without (or only minimal) intra-core instrumentation are planned, to explore conditions that may impact the long-term performance of a clay-based seal, by changing a single parameter at a time with respect to a base case (see also Table 1):

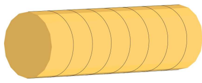
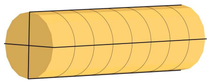
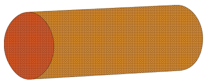
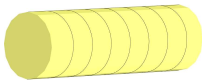
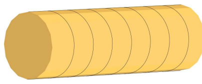
- The first test (PT-N1, see Figure 2) is a base case test itself, with a core build of monolithic precompacted disks (70/30 MX80/sand mix).
- Three tests designed to quantify, with respect to this base case, the impact of the technological choices retained for the engineered barrier. Modifications will concern the intra-core geometry (jointed disks), the core composition (MX80/sand ratio) and the core conditioning (precompacted vs. in situ compacted):
  - The intra-core geometry in test PT-N2 (jointed vs. monolithic disks, both precompacted);
  - The core composition and conditioning in test PT-N3 (core made of pure MX80 pellets/powder compacted in situ vs. 70/30 mix precompacted monolithic disks);
  - The core composition in test PT-N4 (low MX80/sand ratio vs. reference one 70/30);

- Last, a test (PT-A1) to quantify the influence of altered conditions (saturation defect and confining plug failure) with respect to this base case.

3.2 Reference tests

The reference tests aims at quantifying the hydro-mechanical fields (swelling pressure, pore pressure, water content or water saturation) within the core and their time-evolution as the core saturation proceeds, without any restriction on the sensor type. They are therefore a complement to the performance tests (see also Table 1).

Table 1. Summary of the different tests foreseen in the SEALEX project

	Performance tests	Reference tests	Intra-core geometry Core conditioning Core composition (MX80/sand)	Core view	Altered conditions
Base Case	PT-N1	RT-1	Monolithic disks Precompacted (70/30)		No
	PT-N2	-	***Jointed*** disks (4/4) Precompacted (70/30)		No
Variations w.r.t. the Base Case	PT-N3	RT-2	***Pellets/powder*** ***Compacted in situ*** ***(100/0)***		No
	PT-N4	-	Monolithic disks Precompacted ***(20/80)***		No
	PT-A1	-	Monolithic disks Precompacted (70/30)		***- Saturation defect*** ***- Confining plug failure***

4 FURTHER WORK

The SEALEX experimental programme has been built to allow systematically exploring conditions that may impact the long-term hydraulic performance of a clay-based seals, by changing a single parameter at a time with respect to a base case. Attention has also been paid to overcome some difficulties met in past in situ experiments such as the water tightness of the interface between the host-rock and the confining plug.

Emplacement of these in situ experiments is foreseen from mid-2010 and should last over three years (see planning in Table 2). Execution of the hydraulic measurements (i.e. permeability tests) will depend on the real saturation kinetics, and could be carried out few years after emplacement at the earliest.

Table 2. Planning of the SEALEX in situ tests

Date	Test Id	Main characteristics
06/2010	RT-1	Precompacted MX80/sand monolithic disks
12/2010	PT-N1	Precompacted MX80/sand monolithic disks
06/2011	PT-A1	Unloading test for precompacted MX80/sand monolithic disks
12/2011	PT-N2	Precompacted MX80/sand with internal radial joints
06/2012	RT-2	In situ compacted pure MX80
12/2012	PT-N3	In situ compacted pure MX80
06/2013	PT-N4	Precompacted MX80/sand with high sand content

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