SELFRAC	Fractures and self-healing within the excavation-disturbed zone in clays	
Type of test: Clay characterisation	**Collaborating partners:** NAGRA (CH), L3S (FR), G3S (FR), KUL (B), EPFL (CH), SOLEXPERTS (CH) *EURATOM Framework Programme Contract No.: FI4W-CT96-0028*	**Period:** 2001-2004

BACKGROUND

In Belgium, the proposed solution for long-term management of high-level and long-lived radioactive waste is geological disposal in poorly indurated clay. The clay host rock plays a crucial role for the long-term safety of people and the environment. After degradation of the engineered barriers around the waste packages, the clay host rock must continue to contain the waste safely and retard the migration of radionuclides towards the biosphere.

The construction and operation of an underground repository will inevitably cause “damage” in the surrounding host rock, which might have an impact on the migration of radionuclides that enter the host rock after degradation of the engineered barriers. More specifically, excavation might significantly increase the rock’s permeability, related to diffuse and/or local crack proliferation in the material. Self-sealing properties of clays can in turn reduce permeability over time. Proper evaluation of the damaged zone near the repository and its hydro-mechanical and geochemical evolution with time is therefore needed.

The SELFRAC project was carried out as part of the 5th Framework Programme of the European Commission (FIKW-CT2001-00182) and coordinated by EIG EURIDICE. Two different potential geological formations for deep radioactive waste repositories were investigated by means of laboratory tests combined with in-situ tests: the indurated Opalinus Clay at Mont Terri (Switzerland) and the plastic Boom Clay at the HADES URL (Belgium).

During the subsequent construction phases of the HADES URL, the presence of fractures was investigated. At about the same time as the start of the SELFRAC project, the HADES URL was extended with an 80-metre long gallery, connecting the new second shaft with the existing URL. During the construction of this gallery, a great deal of effort was expended on the characterisation of excavation-induced fractures (Bastiaens et al., 2003; Mertens et al., 2004). A consistent fracture pattern was recognised (Figure 1). The pattern consists of two conjugated fracture planes. The distance between successive fracture planes was usually a few decimetres. Examination of clay cores indicated a radial extent of 1 m at most; the extent determined on vertical cores was somewhat lower than on horizontal or inclined cores.

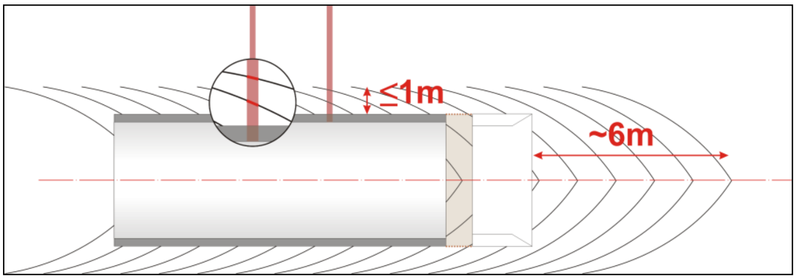

Figure 1 - Vertical cross-section of the observed fractures around the Connecting gallery; their radial extent is up to 1 m and the fractures originate about 6 m ahead of the excavation face.

Early in the SELFRAC project it became clear that one of the first tasks was to define clear terminology, since no international consensus existed on this particular issue. A distinction was made between the Excavation-Damaged Zone (EDZ) and the Excavation-disturbed Zone (EdZ):

- The *Excavation-disturbed Zone* (EdZ) is defined as a zone with hydro-mechanical and geochemical modifications, without major changes in flow and transport properties. Within the EdZ there are no negative effects on long-term safety.
- The *Excavation-Damaged Zone* (EDZ) is defined as a zone with hydro-mechanical and geochemical modifications inducing significant changes in flow and transport properties. These changes can, for example, include one or more orders of magnitude increase in flow permeability.

"Sealing" and "Healing" were also clearly defined right from the beginning of the project:

- Sealing is the reduction of fracture permeability by any hydro-mechanical, hydro-chemical, or hydro-biochemical processes.
- Healing is sealing with loss of memory of the pre-healing state. Thus, for example, a healed fracture will not be a preferential pathway for new fracturing just because of its history.

OBJECTIVES

The SELFRAC project aims to properly characterise the EDZ and its evolution with time. The main objective is to understand and quantify the fracturing, sealing and healing processes and to assess their impact on the performance of geological radioactive waste repositories.

As part of the SELFRAC project, various in-situ experiments have been performed in HADES:

1. EC SELFRAC in-situ test III: Evaluation of the evolution of the Excavation-Damaged Zone around the Connecting gallery, using two parallel piezometers;
2. EC SELFRAC in-situ test IV: Evaluation of the evolution of the Excavation-Damaged Zone around a partially cased borehole using seismic and acoustic measurement techniques;
3. Observations and experiments using piezometers around HADES:
    a. Pore water pressure build-up and distribution
    b. In-situ permeability tests in the filters installed in the boreholes drilled from Ring 55 of the Connecting gallery

1. EVALUATION OF THE EVOLUTION OF THE EDZ USING TWO PARALLEL PIEZOMETERS (EC SELFRAC in-situ test III)

This test involves studying the evolution of hydro-mechanical properties within the EDZ around the gallery after its construction, and is specifically aimed at detecting whether there are any preferential pathways along the gallery (connectivity of fractures).

DESIGN and INSTALLATION

For this purpose, two upward, parallel multi-piezometers[1] 5.6 m long (1 m apart) were installed in rings 62 and 63 of the Connecting gallery (Figure 2) to measure the pore water pressure in the host rock. Since the main purpose of these two piezometers is to study the interconnectivity of fractures, the standard piezometer design had to be altered slightly. Consequently, the distance between successive filters was kept as small as possible. In this way, almost the entire 5.6 m is covered with filters, reducing the possibility that fractures around the gallery intersect with the piezometer (tubing) in between two filters and thus increasing the chance of detecting possible preferential pathways along the gallery.

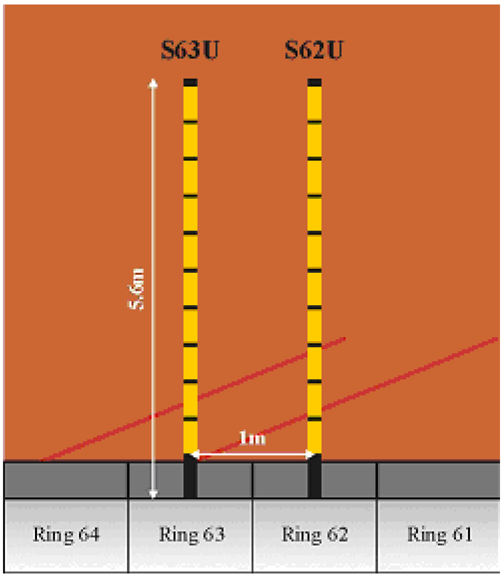

Figure 2 - Layout of the in-situ test. Two parallel multi-piezometers (porous filters in yellow) are installed in the Connecting gallery. Possible fractures are schematically represented in red.

TIMING

March 2002	End of the construction of the Connecting gallery
April 2002	Installation of two parallel multi-piezometers
August 2002	Measurements started
April- September 2003	Hydraulic testing of the filters

[1] Piezometers are metallic tubes, which are installed in a drilled borehole; at several locations the tubes are porous, which allows pore water pressure to be measured at those locations. No packers are used; instead, the filters are sealed off by natural convergence of the borehole walls around the instrument.

RESULTS

For experimental reasons, the design of these piezometers was very specific and the results are more qualitative than quantitative. To examine the interaction between the two piezometers, a pressure change was applied at one filter and the response of the others was observed. In general, the response of filters on the same piezometer was immediate and strong and the response of filters on the other piezometer consisted of two components: a small immediate reaction and a larger but postponed reaction. It may be concluded that a strong hydraulic interaction exists between the two piezometers (~1 m apart). However, there is no interconnected fracture network between them (at least at the tested intervals), as the reaction from one piezometer to the other is delayed. Moreover, the response is different from the imposed input.

2. EVALUATION OF THE EVOLUTION OF THE EDZ USING SEISMIC AND ACOUSTIC MEASUREMENT TECHNIQUES (EC SELFRAC in-situ test IV)

DESIGN and INSTALLATION

The purpose is to monitor closure and self-healing of the clay host rock around a freshly excavated borehole which is (partly) allowed to collapse, by means of seismic and acoustic measurements.

The experiment was set up in the western sidewall of the ANDRA gallery of HADES. Figure 3 and Figure 4 show the borehole arrangement between rings 32 and 36 of the ANDRA gallery. Around a central borehole, four observation boreholes are located.

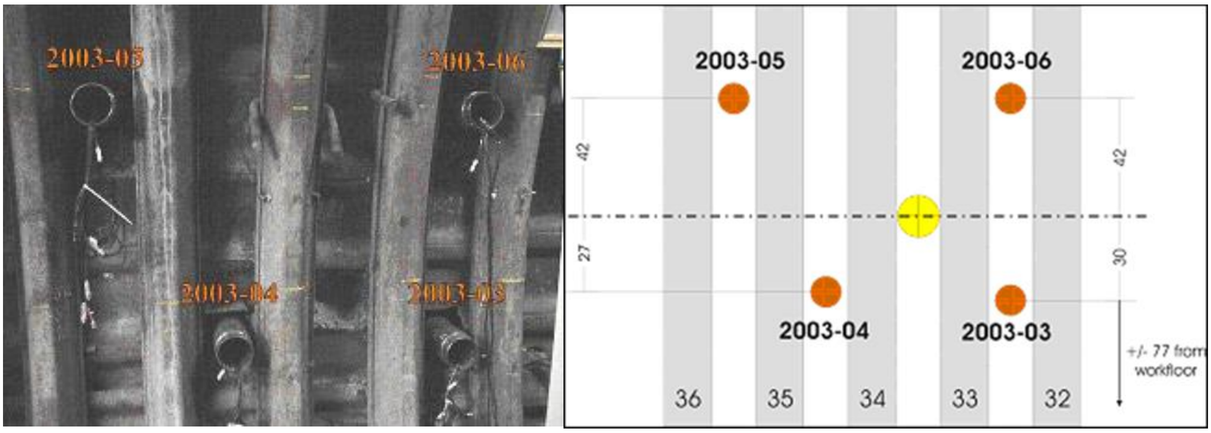

Figure 3 - View of the four instrumented boreholes in HADES-ANDRA gallery (left); schematic representation of the four instrumented boreholes (orange) and the central borehole (yellow) (right).

The observation boreholes are 8.2 m deep and the sensors are located between 5 m and 8 m depth. In each of the boreholes, two receivers and three transmitters are placed and they are oriented towards the central borehole. The drilling diameter is 117 mm, and the casing diameter 108 mm. The central hole is 9 m deep and the collapsing part is located between 5 m and 8 m depth. The drilling diameter of the central hole is 157-160 mm, in the collapsing part the diameter is 108 mm, and in the rest of the tubes the diameter is 152.4 mm. Four transmitters and four receivers (not shown on picture) were installed in liner tube segments in the middle and at both ends of the collapsing part of the borehole. The closure of the borehole is determined in horizontal and vertical direction in the middle of the collapsing part by measuring the force of a loaded compressional spring due to radial convergence.

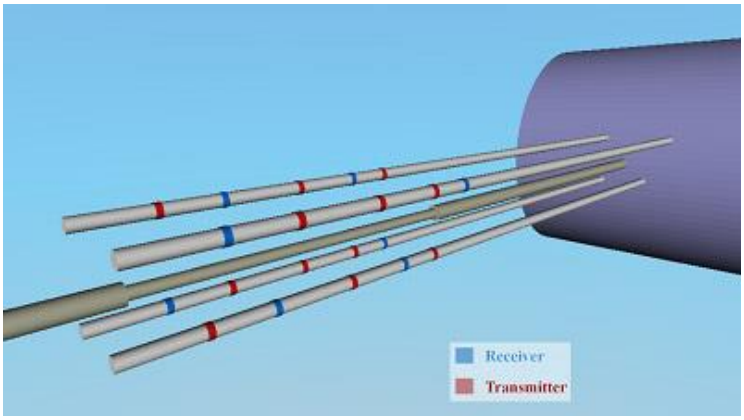

Figure 3 - 3D layout: four instrumented boreholes (each with two receivers and three transmitters) and central borehole.

During the first stage (December 2003), the four observation holes were drilled and instrumented. This made it possible to subsequently investigate the re-stabilisation of the host rock by means of seismic and acoustic measurements. After this period (around May 2004), the central borehole was drilled and instrumented.

TIMING

December 2003	First installation phase of the seismic and acoustic measurements: four instrumented boreholes
May 2004	Installation of the central borehole

RESULTS

The long-term seismic and acoustic measurements are able to reveal disturbances and detect the evolution of sealing/healing processes with time in the Boom Clay by measuring the associated variations in seismic velocities, damping of amplitudes and frequencies of the seismic signals. The collapse of an uncased borehole entails a decompression of the surrounding clay, which leads to an increase in deviatoric stresses and a decrease in pore water pressure. Both effects can result in a decrease in seismic velocities and amplitudes, which was observed in the seismic measurements. After the decompression phase, both the stresses and the pore water pressure tend to recover. Due to ongoing reconsolidation, the acoustic transmissibility of seismic waves increases again in the Boom Clay. The increasing trend was more evident in the seismic amplitudes than in the seismic velocities.

3. OBSERVATIONS AND EXPERIMENTS USING PIEZOMETERS AROUND HADES

3.1. Pore water pressure build-up and distribution

DESIGN and INSTALLATION

In order to monitor the evolution in pore water pressure around the Connecting gallery, a network of five so-called reference piezometers were installed around the gallery shortly after construction of the Connecting gallery. Three piezometers are located at ring 55, and two at ring 13.

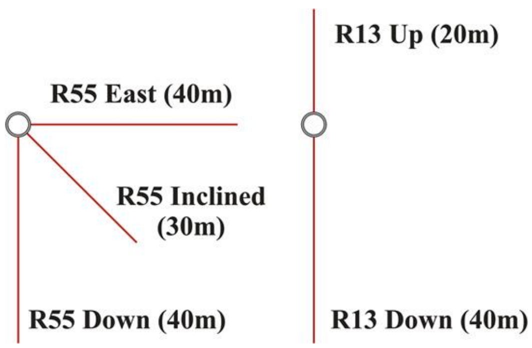

Figure 4 - Reference network of piezometers around the Connecting gallery

TIMING

March 2002	End of the construction of the Connecting gallery
May 2002	Installation of R55E and R55 D
December 2003	Installation of R55I, R13U and R13D

RESULTS

It is clear that the pore water pressure distribution around the Connecting gallery is anisotropic. In the short term after construction of the gallery, the pore water pressure distribution is mainly controlled by the stress redistribution due to the gallery excavation. Since the ratio of the horizontal total stress to the vertical total stress is approximately 0.9, the response of the host rock to excavation will be different in a vertical plane than in a horizontal one. The mean stress will be higher in a horizontal plane than in a vertical one. Due to the low hydraulic conductivity K, the immediate response of the host rock can be regarded as undrained. As a consequence of the undrained response on the stress redistribution caused by the gallery construction, pore water pressures increase left and right of the gallery and decrease above and below it. Over the long term (several years: re-equilibrium of pore water pressures due to dissipation of over- and under-pressures takes several years and depends mainly on hydraulic diffusivity), the influence of hydraulic conductivity (cf. horizontal K_H = ~2* vertical K_V) becomes important. Drainage from the gallery is larger horizontally than vertically.

At the end of 2004, pore water pressure could be measured as little as 30 cm into the host rock (the closest available measuring point), indicating that no unsealed fracture network exists beyond (at most) a few decimetres into the host rock. Moreover, since no packers are used, the filters are sealed off by natural convergence of the borehole walls around the instrument.

3.2. In-situ permeability tests in R55D and R55E

DESIGN and INSTALLATION

The in-situ hydraulic conductivity was derived from single-point constant-head tests in a steady-state flow regime on the filters from boreholes R55D and R55E (Fig. 5). Each piezometer filter is connected to the gallery by a twin tube system; one tube is used to measure the water pressure, the other to inject (or extract) water. A pressure controller imposes a constant pressure at the piezometer filter in the host rock. Once the injection pressure is applied to one tube, the pressure transducer connected to the other tube immediately measures the applied pressure. Both tubes are connected to the same filter and they should therefore have the same pressure. The outflow (inflow) from (into) the clay formation is monitored continuously using a precision balance. Pressure is imposed until steady-state flow has been reached for several days. At the end of this period, the average flow rate of the last couple of days is used to calculate the permeability. With the continuously monitored pressure and flow rate, the permeability can then be calculated.

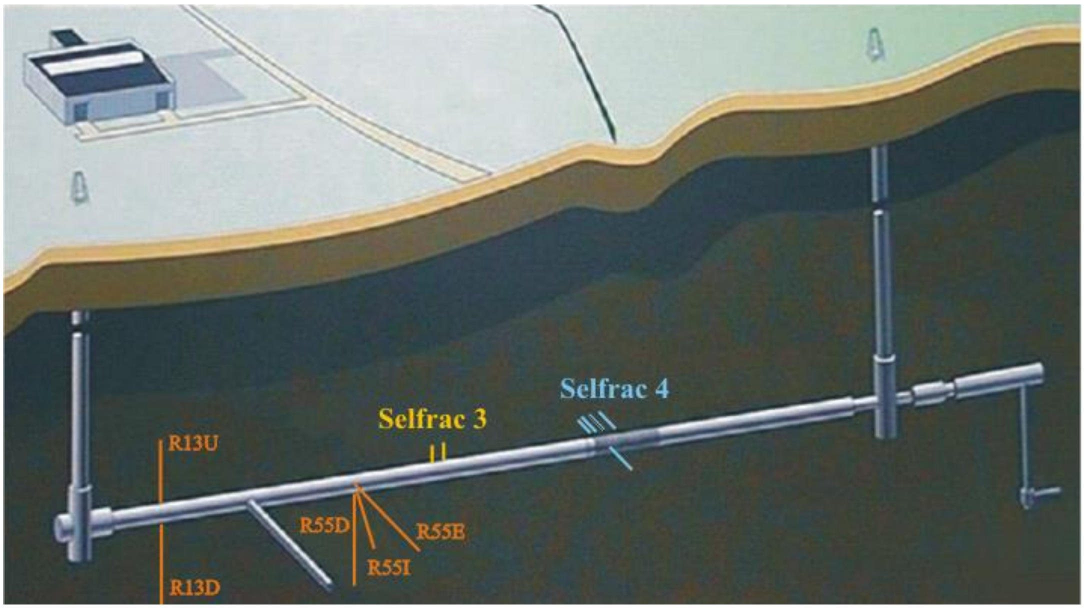

Figure 4 - Experimental set-up of SELFRAC and monitoring boreholes

TIMING

March 2002	End of the construction of the Connecting gallery
May 2004 - approx. November 2005	Two permeability test campaigns in R55D and R55E

RESULTS

The test results are shown in Figure 5. An increase in hydraulic conductivity is observed up to about 6-8 m into the host rock. The values outside this influenced zone are ~6.10^{-12} m/s for the vertical piezometer and ~4.10^{-12} m/s for the horizontal piezometer. About a year after the first measuring campaign on R55D, the first five filters were tested again. The values obtained were systematically lower, although not by much. The first four filters of R55E were also tested again; the values obtained were almost identical to those one year before (slightly lower in the first two filters).

The values outside the influenced zone are consistent with in-situ data obtained in previous experiments. When measuring on a vertical piezometer, K_H is dominant; when measuring on a horizontal piezometer, K_H and K_V are more or less equal. This explains the larger values of k obtained from the vertical piezometer.

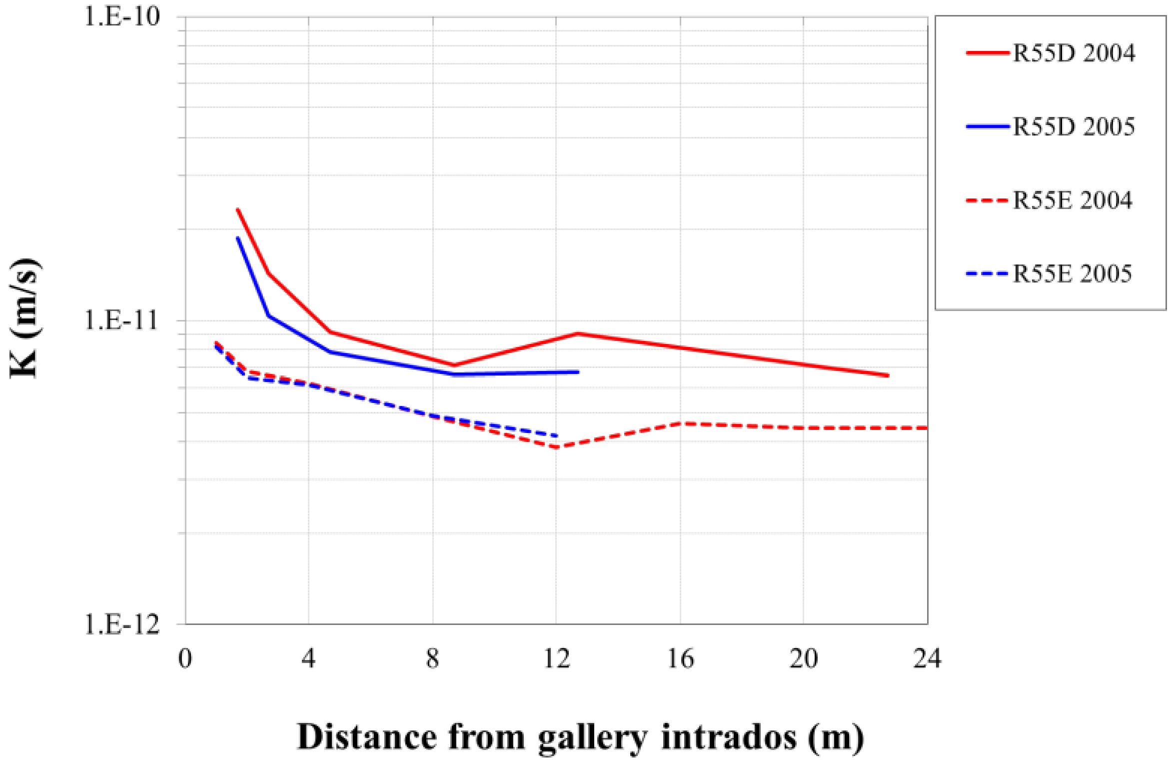

Figure 5 - Constant-head in-situ permeability test results (2004 and 2005).

Based on the test results in Figure 5 and the literature, it can be concluded that effective stress variation alone can account for the variation in hydraulic conductivity measured around the Connecting gallery and that fractures do not play an important role in this case (cf. sealing); almost all measurements were performed further than 1 m into the host rock and thus well beyond the fractured zone. It is important to note that even at the measuring points closest to the gallery, K is only one order of magnitude larger than the undisturbed value.

CONCLUSIONS

The results of in-situ experiments performed in HADES as part of the SELFRAC project clearly show that healing and sealing processes occur in situ in the Boom Clay. This means that the extent of the Excavation-Damaged Zone reduces with time. Consequently, the EDZ will probably not serve as a preferential pathway for the migration of radionuclides in a high-level waste repository.

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