RESEAL	A large-scale in-situ demonstration test for repository sealing in an argillaceous host rock	
Type of test Technical feasibility Sealing of horizontal and vertical drifts	**Collaborating partners**	**Period** 1997 – 2009

BACKGROUND

The construction of the HADES laboratory is important in order to be able to study and demonstrate the technical feasibility of geological disposal in poorly indurated clay formations like the Boom Clay.

The current design by ONDRAF/NIRAS of the repository for geological disposal of category B & C waste consists of vertical shafts that give access to a network of horizontal galleries for transport and disposal of the waste packages (Fig. 1).

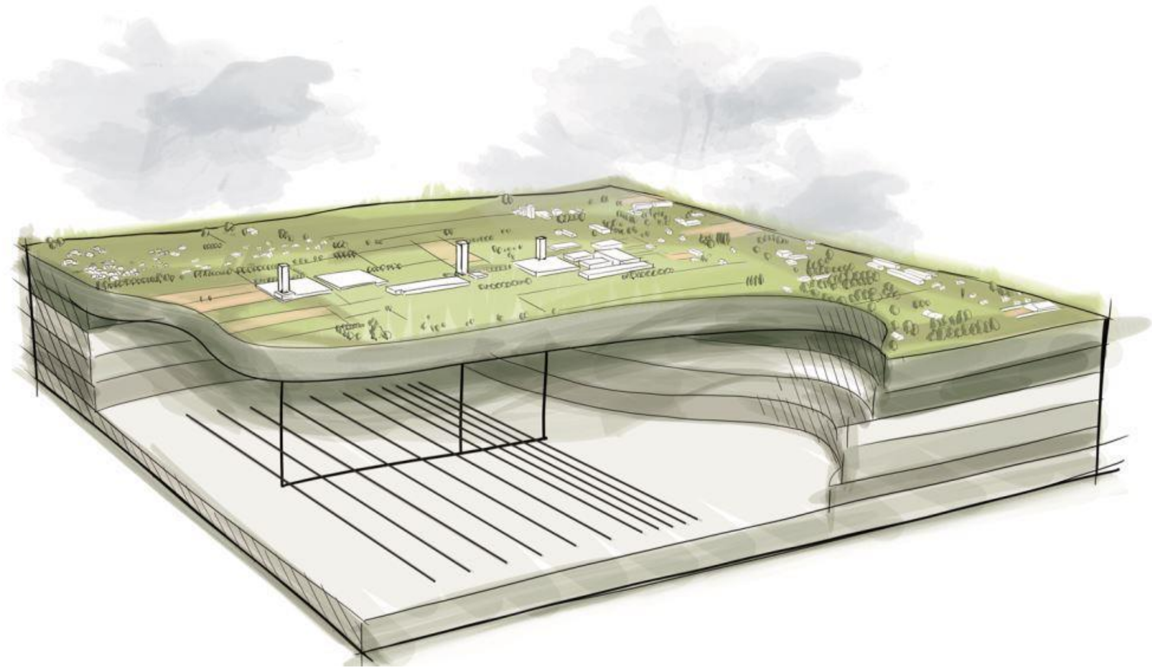

Figure 1 - Artist view of the underground repository (ONDRAF/NIRAS; 2016)

One of the challenges for long-term safety is backfilling and sealing shafts and galleries. This is needed to avoid preferential pathways for water, gas and radionuclide migration. The demonstration of the feasibility of sealing on a representative scale is therefore essential. The applicability of highly compacted bentonite for this purpose has been investigated. The low permeability, swelling capacity and high sorption capacity of bentonite make it a very effective barrier.

OBJECTIVES

The RESEAL project started with a first phase in 1996 within the 4th Framework Programme of the European Commission. The main objectives of this first phase were to:

- Define a procedure for the production and installation of a shaft seal, aiming to install a bentonite seal in a 2 m diameter vertical shaft within the Boom Clay in the HADES URL in Mol, Belgium
- Design, instrument and install the shaft sealing experiment
- Obtain basic parameters on the hydro-mechanical behaviour of the sealing materials
- Install and hydrate a borehole sealing experiment, aimed at sealing a 25 cm diameter horizontal borehole in the Boom Clay in the HADES URL

The RESEAL project was continued with a second phase within the 5th Framework Programme of the European Commission, which started in 2001. The main objectives were to:

- Increase knowledge of the basic parameters influencing the hydro-mechanical behaviour of the sealing material used in the shaft seal
- Evaluate the hydro-mechanical behaviour of the shaft seal and its interaction with the surrounding host rock
- Evaluate the performance of the borehole seal and the shaft seal with respect to water, gas and radionuclide migration

DESIGN & INSTALLATION

BOREHOLE sealing experiment

The experimental set-up consists of a 250 mm diameter and 2.6 m long piezometer installed in the Test drift of the HADES URL between 15 m and 12.4 m behind the lining. Only the first two metres of the piezometer were used for the sealing experiment (Figure 2).

The set-up includes two testing compartments 55 cm in length with a central tube about 56 mm in diameter equipped with filters and total pressure sensors. The compartments are respectively filled with pre-compacted blocks of Serrata clay and FoCa clay installed around the central tube. Total pressure measurements are made using miniature pressure sensors embedded in the set-up. Each filter is equipped with a separate chamber. Two pipes are connected on each chamber, one to a pressure sensor installed in the gallery of the URL; the other is intended for water injection. The lateral faces of the compartments consist of circular filters in which total pressure sensors are incorporated.

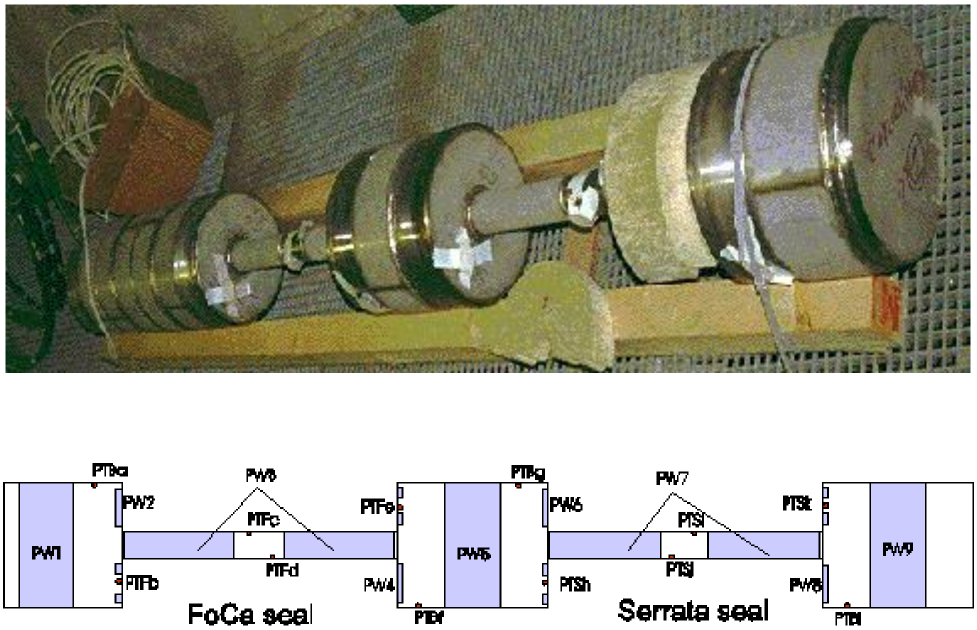

Figure 2 - Picture (top) and technical drawing (bottom) of the experimental set-up, installed at a distance of 15 m from the gallery lining. The empty testing compartments are filled with pre-compacted blocks of Serrata clay and FoCa clay, installed around the central tube

SHAFT seal experiment

Starting from the first gallery of the HADES URL, an experimental shaft and experimental drift were excavated manually in 1984 to demonstrate the possibility of excavating non-frozen plastic clay (Fig. 3).

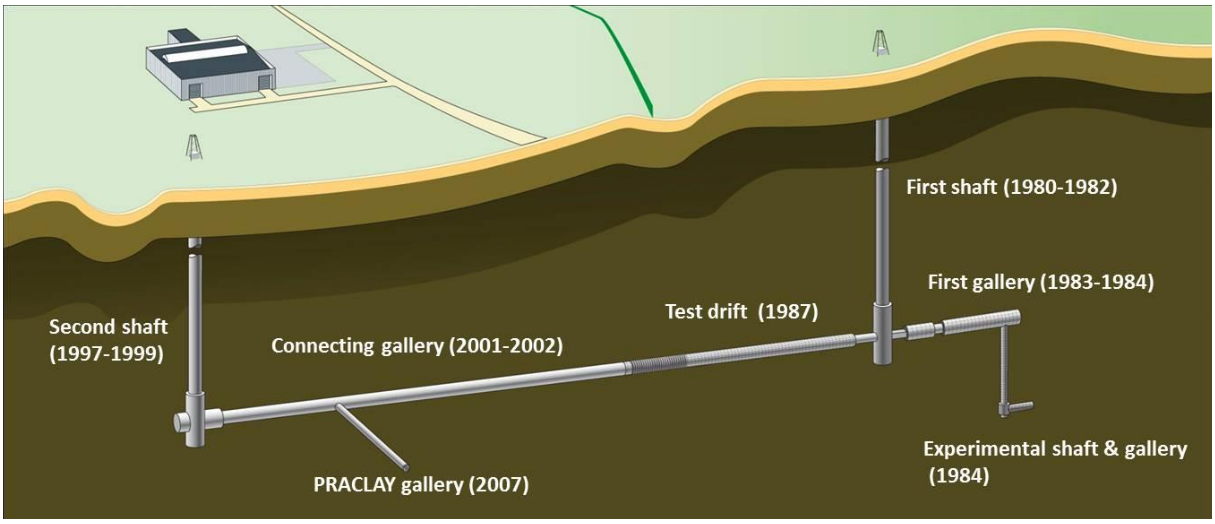

Figure 3 - Layout of the construction of the HADES underground research laboratory

This experimental shaft was chosen for the location of the large-scale in-situ shaft sealing test (Fig. 3). In April 1998, radial piezometers were installed from the experimental shaft into the excavation-damaged zone (EDZ) of the host rock. Figure 4 gives an overview of the experimental set-up. The radial piezometers are situated at mid-height of the bentonite seal. These are 1 m in length and contain several filters to enable the pore water pressure in the host rock to be monitored at several distances from the lining/host rock interface. Very close to these radial piezometers, radial cores were taken for the placement of magnetic transducers between two clay cores for the purpose of monitoring displacement. A vertical piezometer, parallel to the experimental shaft at a distance of about 1 m from the shaft lining, was placed in June 1998. This is also a multi-filter piezometer for pore water pressure monitoring beneath the bentonite seal, next to the seal and above the seal. The bottom of the shaft was filled with a concrete grout.

The mining work for the installation of the seal began in August 1999. The shaft lining was removed over a height of 3.45 m (12.90 to 16.35 m below the HADES URL). After removal of the lining and installation of the first section of the central tube, the shaft was filled with the FoCa bentonite mixture. The first 60 cm of the seal were compacted. The compaction was stopped just below the first instrumented level. From this level the sealing material was installed without further compaction in order to avoid damage to the instruments due to vibro-compaction. On 15 September 1999, a 15 cm layer of sand was placed on the mixture, followed by the hermetic closure of the seal with a resin layer. On top of the resin layer, a reinforced-anchored concrete plug of about 1 m in height was installed.

Different types of instrumentation were used to monitor the test: pore water pressure sensors, total pressure sensors, vertical displacement sensor for the top of the seal and horizontal displacement sensors (magnetic transducers) for host rock displacement and displacement in the seal.

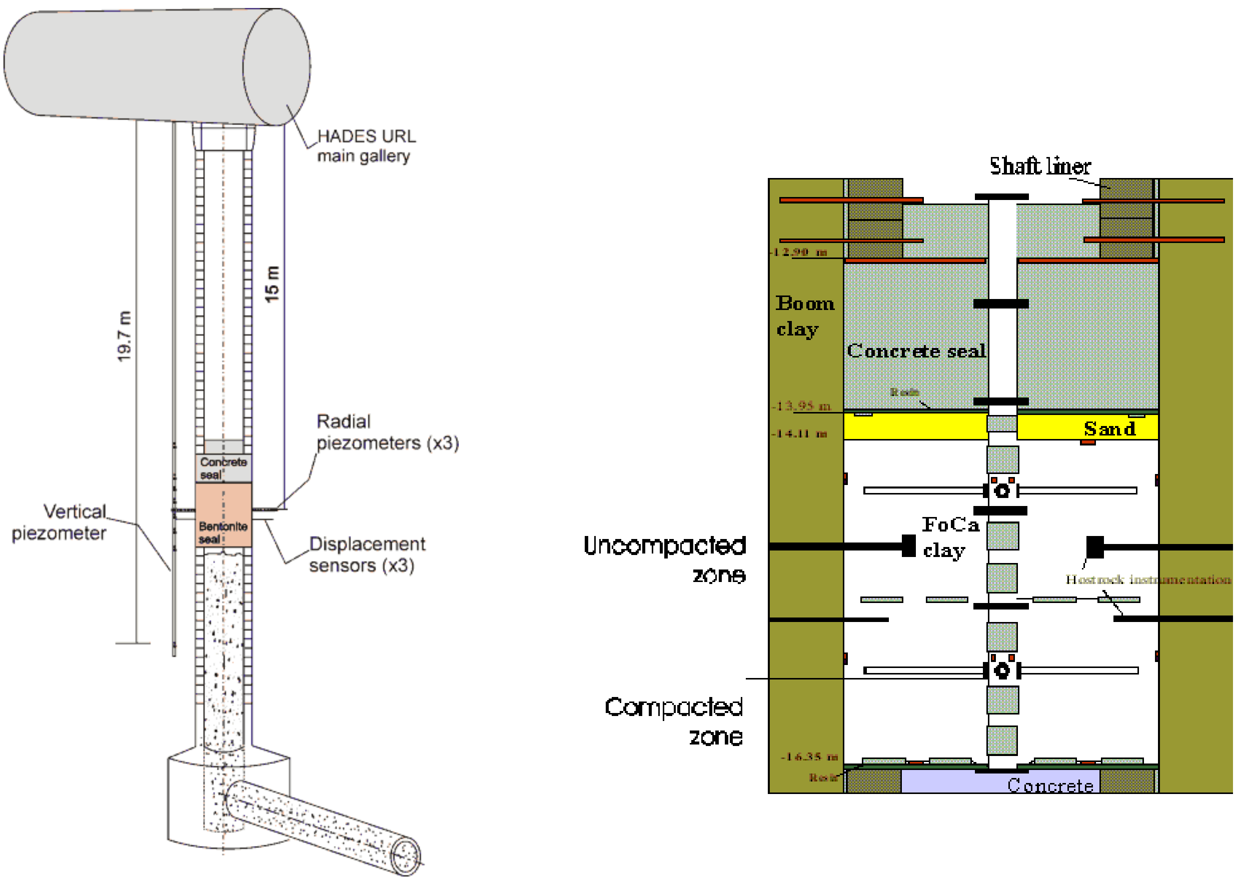

Figure 4 - Experimental set-up of the shaft seal experiment

TIMING

Borehole sealing

- December 1997: borehole drilling, piezometer installation and start of data acquisition
- March 1998: pressure increases measured
- April – September 1998: water injection in the seals (artificial hydration)
- February – March 1999: permeability tests in the seals
- April – September 1999: gas breakthrough experiment (gas injection)
- June 2002 – end January 2004: migration test (^{125}I-labelled NaI tracer injection)

Shaft sealing

- April 1998: installation of radial piezometers and displacement transducers
- July 1998: installation of vertical piezometer
- February 1998: backfilling of the bottom of the shaft with concrete
- August 1999: removal of the lining
- September 1999: installation and closing of the seal
- May 2000: beginning of artificial hydration
- February 2004 – May 2006: hydraulic conductivity tests in seal and Boom Clay
- February 2006 – April 2006: gas injection tests (gas breakthrough tests)
- June 2006: hydraulic shock test at HLB filters
- October 2006: start of migration tests (^{125}I-labelled NaI tracer injection)

RESULTS

Borehole sealing

After hydration of the pre-compacted blocks of FoCa and Serrata clay, the permeability in the borehole seals was measured. A hydraulic conductivity of 4.3 10^{-13} m/s and 5.5 10^{-13} m/s was obtained for FoCa clay and Serrata clay, respectively. These values are 10 times lower than the hydraulic conductivity of undisturbed Boom Clay and are in good agreement with the laboratory measurements at the corresponding dry density. To test the gas sealing ability, a gas injection was carried out. Gas was injected in the host clay formation from a filter close to the FoCa seal compartment at the end of the borehole (PW1 in Figure 2). The gas breakthrough occurred at a pressure level of about 3.1 MPa, i.e. a pressure equal to the radial total stress measured in the FoCa seal. The breakthrough was detected on a filter in contact with the Boom Clay located between the two seals (PW5 in Figure 2), while the pressure sensors connected to the filters in the FoCa seal show a very weak reaction to the breakthrough. This observation shows clearly that the gas did not flow through the FoCa seal towards the nearest filter, but rather flowed along the interface between the FoCa seal and the host rock or through the borehole EDZ of the host rock. Concerning radionuclide migration, comparison of observed concentrations with modelling results does not yield any evidence of the presence of preferential pathways within or around the seal.

Shaft sealing

The shaft seal experiment demonstrated the feasibility of designing and constructing a bentonite shaft seal. It also showed that the time required to obtain full saturation of the seal can be considerable. Furthermore, artificial hydration seems to have only a limited influence on the duration of this process, at least in the current configuration. About 55% of the water volume required for full saturation was injected through the hydration system, but a large degree of uncertainty exists regarding the amount of water that actually contributed to the saturation of the seal (cf. possible leaks). It should be noted that the diameter of the test (~ 2.2 m) is relatively small compared with the access shafts necessary for an actual geological disposal site. Consequently, even larger saturation times could be expected in this case.

At full saturation (18 April 2007), effective stress ranged from 4.5 to 7 bar. Values were somewhat higher for the "east" sensors than for the sensors in the other two positions, mainly due to lower pore water pressures at these locations. This slight non-homogeneity was also evident in the pore water pressure measurements in the host rock. It is difficult to identify a cause for this asymmetry but it might well be due to installation-related issues and may be temporary. An average dry density of 1.41 g/cm^3 was determined for the bentonite shaft seal, resulting in a calculated swelling pressure of 5.8 bar. The measured values of swelling pressure are somewhat higher compared with the calculated ones, but it should be noted that, due to the exponential nature of the equation, small variations in the value of the dry density have a significant impact on the result. Furthermore, calculation of the dry density has to cope with several uncertainties, e.g. the exact excavation profile of the shaft seal.

On average, effective stress (and certainly total stress) measurements are higher in the bottom level than in the top level. This is in line with the higher initial dry density at the bottom part of the shaft seal.

Measurement of total stresses in the host rock proved to be more complicated than in the seal itself. This is in line with previous experience at the HADES URL. The sensors seem to be very sensitive for local and/or temporary phenomena. Furthermore, installation-related issues play an important role. Consequently, the measured total and effective stresses in the host rock should be interpreted qualitatively rather than quantitatively.

The removal of the concrete lining of the shaft has a strong effect on the EDZ. Fractures were formed around the shaft, causing many blocks to fall from the shaft wall during installation of the seal. It is impossible to distinguish between re-activation of existing fractures (caused during excavation) and newly developed fractures caused by removal of the lining. The fractures in connection with atmospheric pressure occur up to at least 1 m into the host rock, but are limited (in height) to a cylindrical zone around the part of the shaft where the lining was removed.

The observed trends and trend changes in the displacement measurements can be related to certain events. Several observations can be linked to the start of artificial hydration (on 3 May 2000). When the first relative humidity sensors inside the seal indicated (local) saturation, the displacement observed close to the centre of the seal changed from outward to inward. When pore water pressure started to increase again in the host rock, the movement of the host rock inverted, and the sensors then moved outward. When pore water pressure inside the seal started to increase, displacements inside the seal seemed to slow down or even stop.

Hydraulic conductivity measurements of the host rock in the course of 2005 and 2006 yielded values in line with those reported in the literature, i.e. of the same order of magnitude as undisturbed Boom Clay, indicating that the seal is performing well. This is true for laboratory measurements made on cores taken prior to the installation of the shaft seal as well as for the in-situ measurements made using the radial piezometers during the shaft seal experiment. The results reflect the known anisotropy of hydraulic conductivity in the Boom Clay ($K_H = \sim 2.K_V$).

Hydraulic conductivities measured inside the seal are of the expected order of magnitude.

Two gas breakthrough tests were performed in the seal, twice using the same injection filter, which floats inside the bentonite seal.

It was observed that breakthrough pressures were twice almost the same: 13.3 bar vs 12.8 bar. Moreover, breakthrough in both cases only occurred a while after the highest pressure was applied. This indicates that the recorded values are at the high end. It cannot be ruled out that breakthrough would have occurred at lower pressures if that pressure had been applied over a longer period of time. In both cases, the most pronounced reactions were observed on the western rod of the bottom instrumentation level. No clear connection between filters was established in either test. The observations made in the second test seem to indicate that a local unsaturated zone existed, or more likely that gas could escape through a leak in the instrumentation.

For plastic clays, it is believed that the breakthrough pressure corresponds with the minimum total stress. The total stresses measured in the seal vary between 7 and 11 bar. Consequently, the measured breakthrough pressures are somewhat higher, but as mentioned before these measured breakthrough pressures should be regarded as maximum values. Moreover, the shut-in pressure observed in the first breakthrough test might be realistic and, at a value of 8.3 bar, lies within the range of total stresses measured inside the seal.

Due to technical limitations of the set-up, the pressure levels in the hydraulic shock test were rather low. Consequently, the test is not fully representative of the situation that was intended to be simulated. However, the influence of increasing the pore water pressure at the bottom hydration level was noticed throughout the entire seal. Total pressure sensors displayed an increase of ~50-100% of the applied pressure increase. Pore pressure sensors also showed a response, but to a lesser extent (~ 25-50% of the applied increase). Sensors in the host rock did not respond. This observation indicated strong HM coupling in the seal.

The radionuclide migration tests in the EDZ seem to indicate that no preferential pathways for radionuclide migration exist.

CONCLUSION AND IMPLICATIONS

The results of the RESEAL project show that it is technically feasible to seal boreholes and shafts in argillaceous media with bentonite products. Pre-compacted bentonite blocks or a mixture of bentonite pellets and powder can be used. However, it takes longer than originally expected to reach full saturation of the shaft seal and artificial hydration only has a limited effect on the time needed to reach a fully or almost fully saturated state.

It could be clearly demonstrated that fractures are created or re-created during removal of the concrete lining. These fractures are limited to a cylindrical zone around the sealed part and extend up to at least one metre inside the surrounding host rock. Although the Boom Clay has a fast self-sealing capacity, there are indications that some fractures remain open as long as hydration of the seal is ongoing. Only when full saturation is nearly achieved are the fractures within the host rock sealed.

PUBLICATIONS

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