

The Belgian Demonstration Programme for the Disposal of High-Level and Long-Lived Radioactive Waste

Bernier Frédéric¹, Demarche Marc¹ and Bel Johan²

¹ESV EURIDICE GIE – European Underground Research Infrastructure for Disposal of Nuclear Waste in Clay Environment, Boeretang 200, BE-2400 Mol

²NIRAS/ONDRAF – Belgian agency for radioactive waste and enriched fissile materials, Avenue des arts, 14, BE-210 Bruxelles

ABSTRACT

The EIG EURIDICE is responsible for performing large-scale tests, technical demonstrations and experiments so as to assess the feasibility of a final disposal of vitrified radioactive waste in deep clay layers. This programme is part of the Belgian Research and Development programme managed by ONDRAF/NIRAS. The research infrastructure includes the Underground Research Facilities HADES (URF HADES) in the Boom Clay geological formation and surface facilities. The achievements of the demonstration programme are the demonstration of the construction of shafts and galleries at industrial scale, the characterisation of the hydro-mechanical response of the host rock, and the "OPHELIE mock-up" a large scale hydration test under thermal load of pre-fabricated bentonite blocks. The future works will consist mainly in the realisation of the "PRACLAY experiments" including a large scale heater test. The large scale heater test has to demonstrate that Boom Clay is suitable, in terms of performance of the disposal system, to undergo the thermal load induced by the vitrified waste. The combined effect of the excavation and the thermal load will be investigated. A long term (more than 10 years) large scale heater test would be representative of the most penalizing conditions that could be encountered in the real disposal. The results of this test will constitute an important input for the Safety and Feasibility Cases 1 (SFC-1, 2013) and 2 (SFC-2, 2020).

INTRODUCTION

The Boom Clay layer, a tertiary plastic clay, was chosen as a study case for the geological disposal of high-level and long-lived radioactive waste. In Belgium, the R&D programme on this topic was initiated at the Belgian nuclear research centre (SCK•CEN) in 1974. The URF HADES was constructed at a depth of 223m for R&D purposes. The first construction phase started in 1980 and since the URF HADES has been expanded several times. Figure 1 shows the construction history. The primary purpose is conducting various in-situ experiments to study the feasibility of HLW disposal in the Boom Clay layer. HADES is currently managed by the Economic Interest Grouping EURIDICE, a joint venture between SCK•CEN and NIRAS/ONDRAF.

Since previous research yielded promising results, the R&D programme is more and more tending towards large scale and demonstration tests. The realisation of the demonstration programme "the PRACLAY project" is the main mission of EURIDICE. The PRACLAY project includes:

- The extension of **URF HADES** consisting in the construction of a second shaft, a connecting gallery and the ventilation building leading to the demonstration of the industrial process for constructing the underground disposal infrastructure;
- The *in-situ PRACLAY experiments* aiming to demonstrate that Boom Clay is suitable, in terms of performance of the disposal system, to undergo the thermal load induced by the vitrified waste;
- The *surface PRACLAY experiments* to demonstrate the technical construction and placement of the engineered barriers, as well as researching the interaction of these with the host rock.

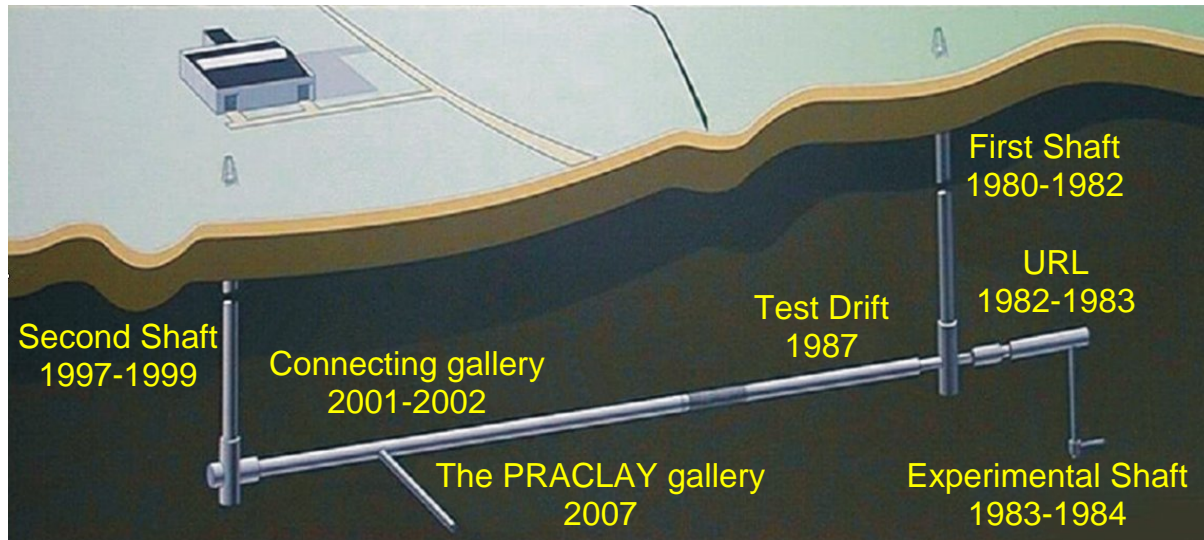


Figure 1. The construction history of HADES

THE EXTENSION OF THE URF HADES

The demonstration that we can construct a repository infrastructure, using an industrial technique, while controlling the disturbances at an acceptable level in terms of performance of the disposal system, is now well advanced with the experience gained with the construction of the HADES extension. The extension consists in the realisation of a second shaft (1997-1999) and the construction of a connecting gallery (2001-2002).

The hydro-mechanical behaviour of Boom Clay around the excavation and its evolution with time is now well characterised and the high sealing capacities of Boom Clay have been proven [1].

The second shaft

The second shaft has an effective diameter of 3 m and widens out to an effective diameter of 5m at low level. The ground freezing technique was used to sink the shaft through the water-bearing sands. In this section the definitive lining consists of prefabricated concrete rings with an 8-mm thick outer steel casing. The gap between the preliminary lining and the definitive lining was filled with asphalt. The part in Boom Clay was realised without freezing [2]. In this section the definitive lining consists of poured concrete in direct contact with the Boom Clay.

The feasibility of digging in unfrozen Boom Clay from the top (-190 m) to the middle (250 m) of the Boom Clay layer has been demonstrated. During the excavation of the second shaft, the mechanical behaviour of the rock was quite homogeneous, irrespective of the depth. During the construction of the starting chambers, significant slip planes were observed. Their symmetry around the shaft axis indicated that the fractures were induced by the excavation work. Active support installed immediately after the excavation considerably reduced the opening of the fractures and the risk of detachment of blocks.

The connecting gallery

The construction of the connecting gallery by an industrial technique has been an important milestone in the demonstration programme for the disposal of high-level radioactive waste. The construction with a tunnelling machine represented a real challenge indeed, since it required a very good knowledge of the response of the rock: a non-optimal design could have led to the tunnelling machine getting trapped in the Boom Clay because of convergence.

Four main requirements were set to limit the extent of the zone disturbed by excavation: maximising the construction rate, minimising the overexcavation, minimising the length of the unsupported zone, and choosing a stiff lining.

The construction of the connecting gallery required the prior construction of a mounting chamber, namely of a chamber that would be large enough to enable the tunnelling machine and the associated equipment to be assembled. The tunnelling machine (see figure 2) was composed of three main parts: a road header to excavate the rock, a 2.3 metre long shield to protect the workers and control the convergence, and a bird-wing erector to install the lining segments. The excavated diameter by the road-header was slightly smaller than that of the shield. It was therefore the shield that imposed the final, smooth excavation profile. The lining technique was the wedge block technique, an expandable-lining technique thought to be suitable for lining galleries in the Boom Clay at about 223 metres depth while minimising convergence. Each lining ring consisted of ten 40-cm thick concrete segments and two smaller, trapezoid shaped keys, the insertion of which expanded the ring against the excavated profile. The nominal external diameter of the rings was 4800 mm [3].



Figure 2. The tunnelling machine used for the construction of the connecting gallery

The accompanying scientific programme (CLIPLEX project) has shown that the disturbances around the connecting gallery were kept at an acceptable level for the long-term safety of the repository. Indeed, it has been shown that the hydraulic conductivity in the EDZ will be at the maximum one order of magnitude higher than that of intact clays. The average construction rate reached 3 metres a day, with a peak of 4 metres on one day. In the future, this construction rate could easily reach 10 metres a day with minor adaptations to the excavation technique and considering a larger access shaft. The construction of the connecting gallery has thus been a great success and constitutes an important step forward in the development and design of an underground repository for radioactive waste.

The CLIPLEX project

The excavation of the connecting gallery from the second shaft towards the existing Test Drift provided a unique and original opportunity to monitor the hydro-mechanical parameters of Boom Clay ahead of an excavation front. The EC CLIPLEX instrumentation programme (Clay Instrumentation Programme for the Extension of an Underground Research Laboratory) enabled the instantaneous hydro-mechanical response of the clay during excavation of the connecting gallery to be characterised with high reliability [4]. The host rock has been instrumented both in the zone to be excavated and around it.

The numerical simulations using Mohr-Coulomb and Modified Cam-Clay models gave reliable blind predictions in terms of displacement and pressure on the lining thus allowing an optimum design of the tunnel machine. One important finding of the project is the unpredicted observation of hydraulic perturbation deep inside the formation. Current model developments are made to explain the variation of pore water pressure in the far-field (about 60m from the excavated front) considering the delayed effects through the viscosity of the Clay skeleton.

The SELFRAC project

The SELFRAC project aims to properly characterise the Excavation Damaged Zone (EDZ) and its evolution with time. The perturbation of the excavation may lead to a significant increase of the permeability, related to diffuse and/or localised crack proliferation in the material. Fortunately, an opposite process, which involves the sealing properties of clays can in turn reduce the permeability in time. The main objective of the project is to understand and to quantify these processes and to assess its impact on the performance of radioactive waste geological repositories. The SELFRAC project is also a key issue to improve constitutive models designed to increase public confidence in long-term predictions of the behaviour of a deep nuclear waste repository.

An important achievement of the project is the clarification of the terminology. There is now an international consensus to relate the definition of the EDZ with the long-term safety of a geological disposal pointing out that hydro-mechanical and geochemical perturbations can occur without major changes in flow and transport properties. A clear distinction is now made between the Excavation disturbed Zone (EdZ) and the Excavation Damaged Zone (EDZ) [5]:

- The Excavation Disturbed Zone (EdZ) is 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 the long-term safety.

- The Excavation Damaged Zone (EDZ) is 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.

Triaxial and biaxial tests were developed to understand and quantify the fracturing process in Boom Clay and the increase of permeability related to crack proliferation around excavations. The results of these tests have allowed to establish the sets of parameters for the numerical simulation.

Other tests were conducted to characterise the sealing process by monitoring the evolution of the flow properties along a fracture. Results of these tests show that for Boom Clay sealing occurs very quickly after the flooding of the fracture. During the sealing process the permeability decreases up to value close to the permeability of intact Boom Clay (about 4.10×10^{-12} m/s). These results have been confirmed through in-situ tests.

THE IN-SITU PRACLAY EXPERIMENTS

The Belgian design for the disposal of the vitrified High-Level radioactive Waste considers the host-rock as the main barrier for the long term isolation in the normal evolution scenario. The effect of a large scale thermal load on the behaviour of Boom Clay is one important remaining issue in the feasibility study of the disposal. Indeed, the impact of the thermal load generated by the waste is particularly important since it will significantly affect the temperature and the stress profiles on the whole thickness of Boom Clay in the short term after the disposal. Therefore the early transient THM perturbation might be the most severe impact that the repository system will undergo on a large spatial scale and in a relatively short period of time.

The PRACLAY in-situ experiments is developed to be design-independent to overcome possible future changes in the reference disposal design. The PRACLAY experiments are performed within “The PRACLAY Gallery”, which will be 45 m long with an internal diameter about 2 m, lined with concrete segments and perpendicular to the connecting gallery. The heater length will be about 30 m. The PRACLAY in-situ experiments regroups a set of three tests (see figure 3):

- The gallery and crossing test
- The heater test
- The plug test

The Gallery and Crossing Test

The construction of a gallery is necessary to host the PRACLAY In Situ Test. The excavation method will be similar to the excavation method used for the connecting gallery. The excavation will be performed under the protection of a shield and using the wedge block system for the lining. The method has to allow an excavation rate (excavation + installation of the lining) greater than 2m/day. At the end of the gallery a test will be done to assess the difficulty to restart with the tunnelling machine after a stopping period.

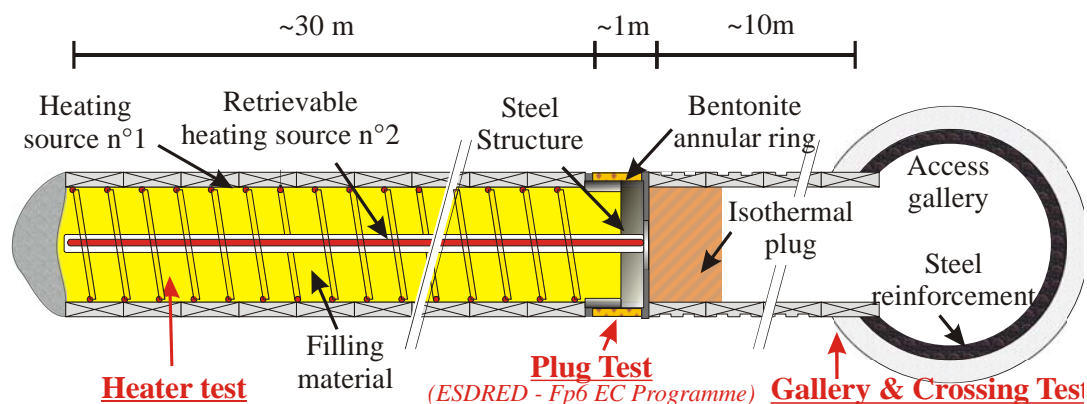


Figure 3. The PRACLAY experiments

The construction of the PRACLAY gallery requires a steel reinforcement ring in the connecting gallery. The maximum possible diameter for the opening in the connecting gallery is 2.55 m. Consequently, the nominal diameter of the extrados of the PRACLAY gallery has been fixed to 2.5 m taking into account the convergence. A diameter about 2.5 m corresponds to the range of diameters considered for the repository designs.

The results of the gallery and crossing test will give additional information for the optimisation of the tunnel excavation and will demonstrate the feasibility to construct a crossing between an access gallery and a disposal gallery.

The Heater Test

A large scale heater test is considered as a generic issue for all repository design since at a distance larger than a few metres from the waste, the influence of the specific design on the temperature profile is limited.

The large scale heater test has to demonstrate that the damaged zone of the host rock remains acceptable in terms of long term performance of the repository. It will be important to verify that fracturation remains acceptable and that the decrease of effective stress due to the increase of pore water pressure will not lead to the liquefaction of Boom Clay. The impact of the chemical processes on the transport properties of the Boom Clay will also be investigated.

A long term (at least 10 years) large scale heater test would be representative of the most penalising conditions that could be reached in a real disposal. However preliminary conclusions could already be drawn quickly (one year) after the start of the experiment.

It has been chosen for the PRACLAY In Situ Experiment, to use a heater system imposing a as constant as possible temperature of about 80°C at the extrados gallery wall. However a second heater working at constant flux will also be installed as a back up of the first heater in case of failure. This back-up heater can be retrieve during the PRACLAY Heater Test.

The Plug Test

Plugs (within disposal galleries, between disposal and main galleries, between main galleries and shafts) are considered, at least as a conservative measure, in the overall repository design in order to e.g., limit interactions between various repository zones (compartmentalisation through

cutting the hydraulic connection along the gallery lining and EDZ), increase the resilience of the repository to intrusion, and avoid gas migration.

The “PRACLAY Plug Test” aims at demonstrating that it is possible to cut-off hydraulically the EDZ and the engineered barriers of the disposal galleries with a horizontal plug.

THE SURFACE PRACLAY EXPERIMENTS

The PRACLAY Surface Experiments include the feasibility study of the construction and the handling of the engineered barriers. For these tests, it is currently understood that in situ conditions are not required, i.e., that the influence of, and the interactions with, the host formation do not condition the short term performances of the engineered barriers. Hence, it is not primordial to test these elements in situ. It is therefore proposed to test them on surface which should enable better control of the experimental conditions and be more cost-effective.

The OPHELIE mock-up

The OPHELIE Mock-Up simulates a section of a waste disposal gallery, in order to review several technical aspects of the design. The Mock-Up is mainly focused on the engineered barriers of the disposal system: the backfill material (mixture of 60% FoCa clay, 35% sand and 5% graphite), the disposal tube and the hydration system. The Mock-Up also allows a large scale investigation of the THM (Thermo-Hydro-Mechanical) behaviour of the backfill material as well as the interactions with the other barriers. The clay host rock and the gallery lining are simulated by a steel liner design to resist to the internal swelling pressure. The mock-up has an internal diameter of about 2 m and a length of about 5 m. On the inside of the steel cylinder, hydration tubes allow to hydrate the backfill material. Centrally, a tube with dimensions similar to the waste disposal tube contains heating elements that dissipate heat at a power of 450 W/m. The Mock-Up was instrumented with about 150 sensors. The hydration started in 1997 and the heating was switched on six months later [6]. The mock-up has been dismantled in 2002.

The measurements performed during the experiment lead to some unexpected results such as the high apparent thermal conductivity, the low swelling pressure exerted by the backfill material, and the high content of chlorides in the central part increasing the risk of corrosion. Analysis and observation during the dismantling have shown that all technological gaps were filled by the swelling of the bentonite, after 5 years hydration time the bentonite blocks were not fully saturated (saturation about 92%) in the central part and the joints between blocks were still apparent.

The measurements and the observations have led to the change of the temperature criterion inside the engineered barriers ($T < 100^{\circ}\text{C}$ – [7]) and to the reconsideration of the reference design. The lessons learned from the OPHELIE Mock-Up remain however very important and are taken into account for the development of the new alternatives.

The demonstration of the “Supercontainer design”

The demonstration programme has been recently reoriented in respect with the evolution of the Belgian architecture for the disposal of category C waste. ONDRAF/NIRAS selected “the Supercontainer design” as the new reference design by means of a multi-criterion analysis [7]. Although some aspects related to feasibility and technological issues were already, implicitly,

considered during this selection process, the technological feasibility to construct the engineered barriers system (EBS) and its different components remains, to a large extent, still to be demonstrated. This demonstration programme will start in 2006.

CONCLUSIONS

At this time, the study of the feasibility for Boom Clay is well advanced. The effect of a large scale thermal load on the behaviour of Boom Clay is a important key issue remaining to be studied. Indeed the impact of the thermal load generated by the waste is particularly important since it will significantly affect the temperature and the stress profiles on the whole thickness of Boom Clay in the short term after the disposal. Therefore the early transient THM perturbation might be the most severe impact that the repository system will undergo on a large spatial scale and in a relatively short period of time. In order to demonstrate that Boom Clay will behave as predicted under a thermal load a large scale heater test within "The PRACLAY experiments" is planned. The performance of a horizontal plug will be tested in the same experimental drift. The results of these large scale tests will be a milestone in the choice by the Belgian government of a disposal strategy for radioactive waste. Parallel to the in-situ PRACLAY experiments, the feasibility of the new reference design, the "Supercontainer" will be studied.

ACKNOWLEDGEMENT

Some results presented in the paper were obtained in the frame of the CLIPEX and SELFRAC projects. These projects were co-funded by the European Commission within the fourth and the fifth framework programme, key action Nuclear Fission. This support is acknowledged.

REFERENCES

- [1] Bernier F, Sillen X. and Marivoet J., "Lessons learned with respect to EDZ in Plastic Clays", Luxembourg, 3 - 5 November 2003, European Commission Report EUR 21028 EN, 2004
- [2] Bernier F., Buyens M., Brosemer D. and De Bruyn D., "Extension of an underground laboratory in a deep clay formation", GeoEng2000, Melbourne, 2000
- [3] Bastiaens W. and Demarche M., "The extension of the URF HADES: realization and observations", WM'03 Conference, Tucson, AZ, February 23-27 2003
- [4] Bernier F., Ling Li X., Verstricht J., Barnichon J.D., Labiouse V, Bastiaens W., Palut J.M., Ben Slimane K., Ghoreychi M., Gaombalet J., Huertas F., Galera J.M., Merrien K., Elorza F.J. and Davies C., "CLIPEX: CLay Instrumentation Programme for the Extension of an underground research laboratory", Final Report, EUR 20619 EN, 2003
- [5] Bernier F. and Davies C., "Proceedings of a European Commission CLUSTER Conference and Workshop: Impact of the Excavation Disturbed or Damaged Zone (EDZ) on the Performance of Radioactive Waste Geological Repositories", Luxembourg, 3 - 5 November 2003, European Commission Report EUR 21028 EN, 2004
- [6] Dereeper B. and Verstricht J., "The Mock-Up OPHELIE: A large scale backfill test for HLW disposal", International meeting, Clays in Natural and Engineered Barriers for Radioactive Waste Confinement, Reims, 2002
- [7] Bel J., Debock C. and Giovannini A., "Alternative Deep Repository designs for Disposal of Very High-Level Waste in Belgium", WM'04 Conference, Tucson, AZ, February 29- March 4, 2004