2017

Activity Report

ESV EURIDICE EIG

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Approved by:
Hildegarde Vandenhove, Board of Governors
Marc Demarche, Chairman of the Board

Responsible editor
Peter De Preter, Director of the EIG EURIDICE
Sneppenstraat 66, 3010 Kessel-Lo

EIG EURIDICE
Boeretang 200
BE-2400 MOL
Tel. +32 14 33 27 84
www.euridice.be

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General foreword

Marc Demarche, Chairman of the Board of EIG EURIDICE

Dear reader,

EIG EURIDICE is the Economic Interest Grouping of ONDRAF/NIRAS and SCK•CEN, and is responsible for managing and operating the HADES underground research laboratory (URL), conducting research and development activities relating to the geological disposal of radioactive waste in deep clay formations, and communicating about its activities. This Activity Report provides a comprehensive overview of the main developments and achievements with respect to EIG EURIDICE's statutory tasks in 2017.

Since the late 1990s, the PRACLAY project, as part of the RD&D programme of ONDRAF/NIRAS on geological disposal, has been a key priority for EIG EURIDICE. The large-scale PRACLAY Heater test, carried out in the PRACLAY gallery of the HADES URL, is the final stage of this project. The heating phase of this experiment was successfully started in November 2014. In August 2015 the target temperature of 80°C was reached at the interface between the concrete gallery lining and the Boom Clay. This temperature will be kept constant for 10 years, after which the cooling phase and dismantling will follow.

During 2017 the heating phase was continued, successfully completing the second year of heating at 80°C. The numerous measurement devices and sensors in and around the PRACLAY gallery generate a large amount of data and information on the characteristics of all components in the Heater test and their evolution with time (PRACLAY gallery, concrete lining, seal structure, clay). All the scientific findings and results obtained since the start of the Heater test clearly show that the clay is able to sustain the temperature increase without any major alteration of its structural integrity or of its ability to act as an effective barrier for a disposal system. The findings and results generally confirm the "numerical predictions". These predictions were defined using numerical models before the start of the heating phase, and are based on the results of small-scale in-situ heating tests and laboratory measurements. At the end of 2017 EURIDICE published a report containing an initial overview and evaluation of the scientific findings since the start of the Heater test in November 2014.

Besides continuing to manage and follow up the test, the EURIDICE team will focus next year on a detailed scientific assessment of all results obtained, covering the first three years of heating at 80°C and also the period of the highest impacts on the clay (temperature gradients and pore water pressure increases), and on a systematic assessment of the performance of all the measuring devices and sensors used in the test. The results of these assessments will be reported in 2018.

In 2017 EURIDICE also devoted a great deal of effort to knowledge management in the area of measuring devices and sensors through a systematic evaluation of the performance and reliability of measurement sensors in earlier experiments in the HADES URL. The methodological approach was defined and described in detail in 2016 and fully applied in 2017 to the CLIPEX experimental set-up. The results of this assessment were available and reported in 2017.

2017 was a busy year for EURIDICE's communication activities, mainly because of the large number of visitors (2,458), covering a wide range of stakeholders and interested parties. In addition, the scientific sections of the EURIDICE website were completed in collaboration with the scientific team. These give a comprehensive overview of all past and present EURIDICE scientific activities.

With regard to the safety and operation of the facilities, specific efforts were made to improve the technical facilities and prepare for the refurbishment of the shaft 1 hoisting system. In 2017, following a public tendering procedure, an engineering company was contracted to support EURIDICE in the pre-design work and in the definition of the technical specifications for the new hoisting system and the related components (electrical installation, building, shaft lining stability, etc.). EURIDICE also discussed with the safety authorities the applicable regulatory requirements for the new hoisting system.

EURIDICE has continued to contribute to ONDRAF/NIRAS's surface disposal programme for low-level waste in the areas of safety assessments, hydrogeological studies and monitoring/instrumentation.

In 2017, at the request of its constituent members SCK•CEN and ONDRAF/NIRAS, EIG EURIDICE continued a strategic review of the implementation of its statutory tasks, today and in the future. In the course of the year this review led to clear conclusions on the main points that were agreed upon in principle by EIG EURIDICE's Board and constituent members. On the basis of this, a process for the modification of the Statutory Rules and the functioning of EIG EURIDICE in support of its members will be implemented in the first half of 2018, bringing this strategic review to an end.

Marc Demarche, Chairman of the Board of EIG EURIDICE

EIG EURIDICE: history, tasks and fields of expertise

EIG EURIDICE (European Underground Research Infrastructure for Disposal of nuclear waste In Clay Environment) is an Economic Interest Grouping (EIG) involving the Belgian Nuclear Research Centre (SCK•CEN) and the Belgian Agency for Radioactive Waste and Enriched Fissile Materials (ONDRAF/NIRAS). It manages the HADES underground research laboratory and carries out RD&D, including feasibility studies for the disposal of high-level and long-lived radioactive waste in a clay host rock. In this way, EIG EURIDICE contributes to the national disposal programme for high-level and long-lived waste managed by ONDRAF/NIRAS. EIG EURIDICE also contributes, to a more limited extent, to the surface disposal programme of ONDRAF/NIRAS for low-level waste.

In 1974 SCK•CEN embarked on research into the geological disposal of high-level and long-lived radioactive waste in a clay host rock. The Boom Clay, a poorly indurated clay (or plastic clay), was and still is regarded as a potentially suitable host formation. This clay layer is found at a depth of 190 to 290 metres below the SCK•CEN research site in Mol. In 1980 SCK•CEN began construction of the HADES (High-Activity Disposal Experimental Site) underground research laboratory (HADES URL Figure 1), situated at a depth of about 225 metres. This was the first purpose-built underground research facility in plastic clay in Europe and worldwide. The laboratory was gradually extended, with the excavation of a second shaft (1997-1999) and a Connecting gallery (2001-2002) linking the second shaft to the then existing underground laboratory. At each stage of excavation and construction, new techniques were used and new technological and engineering expertise was gained. The HADES URL has been managed and operated by the EIG since 1995.

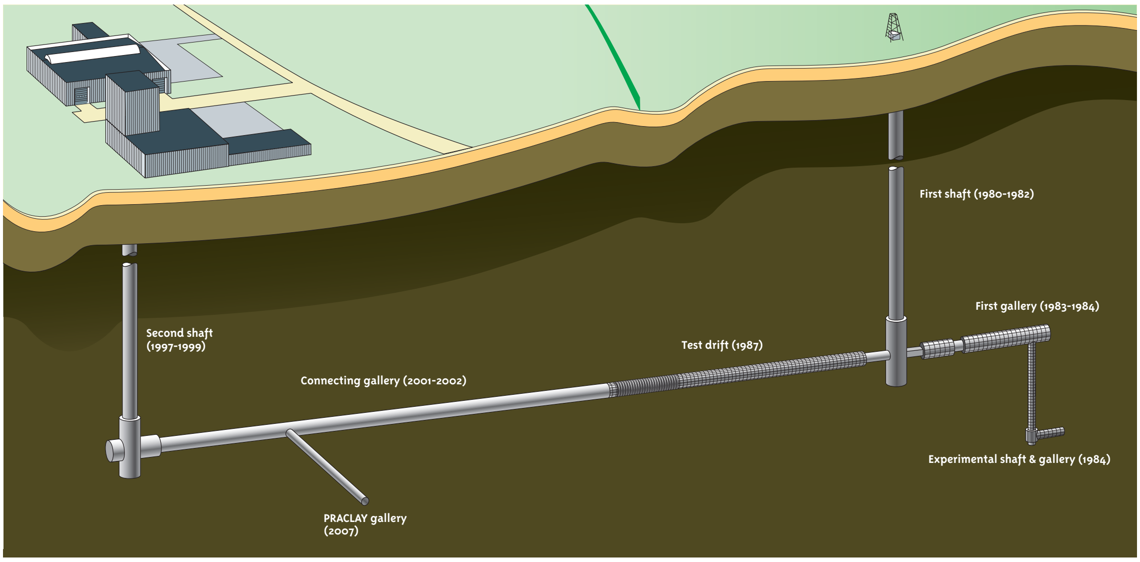


Figure 1 - The underground research laboratory HADES (High-Activity Disposal Experimental Site)

The main statutory tasks of EIG EURIDICE entail a range of activities with a view to developing and facilitating the activities of its constituent members:

- The management and operation of the HADES URL and all the installations situated on the land for which EIG EURIDICE has a building lease.
- The development of the PRACLAY project, which aims to contribute to demonstrating the feasibility of disposal of radioactive waste in a clay host rock.
- The possible development, implementation and valorisation of other research projects and experiments with regard to the disposal of radioactive waste.
- The possible realisation, exploitation and valorisation of other research projects concerning the long-term management of radioactive waste in order to support the scientific programmes of its members using their resources.
- Communication about its own activities, in dialogue with its members, including the organisation of visits to the HADES URL.

After 35 years of research in and around the HADES URL, a great deal of expertise and know-how has been acquired in different scientific and technological fields, of key importance for developing an underground radioactive waste disposal facility in poorly indurated clay formations such as the Boom Clay. The scientific and technological expertise of EIG EURIDICE focuses on three areas:

1. Excavation and construction techniques for an underground repository in a clay host rock.
2. The thermo-hydro-mechanical (THM) behaviour of the clay host rock and engineered barrier system (EBS)
3. Instrumentation & monitoring.

EIG EURIDICE's first area of expertise has changed significantly over the past 35 years, with excavation and construction of the HADES URL evolving from semi-manual and slow to industrial, using tailor-made tunnelling machines. The tunnelling techniques used for excavating in poorly indurated deep clay layer, including the crossing between galleries, have greatly reduced excavation induced disturbance of the clay layer and have demonstrated that it is feasible to construct a disposal infrastructure, at a reasonable speed and cost. Since the natural clay layer will be the main barrier for radionuclide migration in a geological disposal system, reducing the excavation-damaged zone (EDZ) around the excavated galleries is a key objective and relates directly to the safety of a disposal system.

The second field of expertise of EIG EURIDICE involves understanding the thermo-hydro-mechanical (THM) behaviour and characterisation of a clay host rock and engineered barrier system (EBS) (concrete buffer comprising supercontainer, concrete liner, clay-based seal materials such as bentonite, etc.), including all disturbance processes induced by the construction of the galleries and by the emplacement of heat-emitting radioactive waste. In low-permeability clays such as the Boom Clay, THM processes are strongly coupled. EIG EURIDICE's knowledge base is mainly built on the research activities in and around the HADES URL as well as in surface laboratories in collaboration with geotechnical laboratories and institutes worldwide. The extensive scientific instrumentation systems installed in the clay before, during and after the construction of galleries made it possible to create a valuable geotechnical knowledge base and database to characterise and understand the hydro-mechanical response of the Boom Clay in the short and long term, including the generation and evolution of the excavation-damaged zone (EDZ). Proper understanding of the coupled THM processes in a clay host rock around the repository is essential so as to determine to what extent these processes could affect the capacity of the clay to contain the radioactive substances and to isolate the radioactive waste. The most important project in this area is the large-scale PRACLAY experiment. Here, the combination of the hydro-mechanical disturbances due to excavation of galleries and the further coupled thermo-hydro-mechanical disturbance due to heat production, as in the case of the disposal of high-level vitrified waste or spent fuel, are studied on a large scale.

The RD&D programme in and around the HADES URL relies heavily on the use of various instrumentation devices and techniques to measure and monitor the main THM characteristics of the clay; some of these have been developed in-house. This is the third main area of expertise of EIG EURIDICE. Experience has been gained in several aspects specific to this type of instrumentation and monitoring, such as the long-term operation (decades) of sensors and their measurement data, reliability (e.g. how to implement field calibration and what the alternatives are when this is not possible) and robustness under adverse conditions, such as corrosion and mechanical strains. This extensive instrumentation experience will be an essential element for good implementation of future in-situ experiments and in designing a monitoring programme for an underground repository for high-level and long-lived waste in a clay host rock.

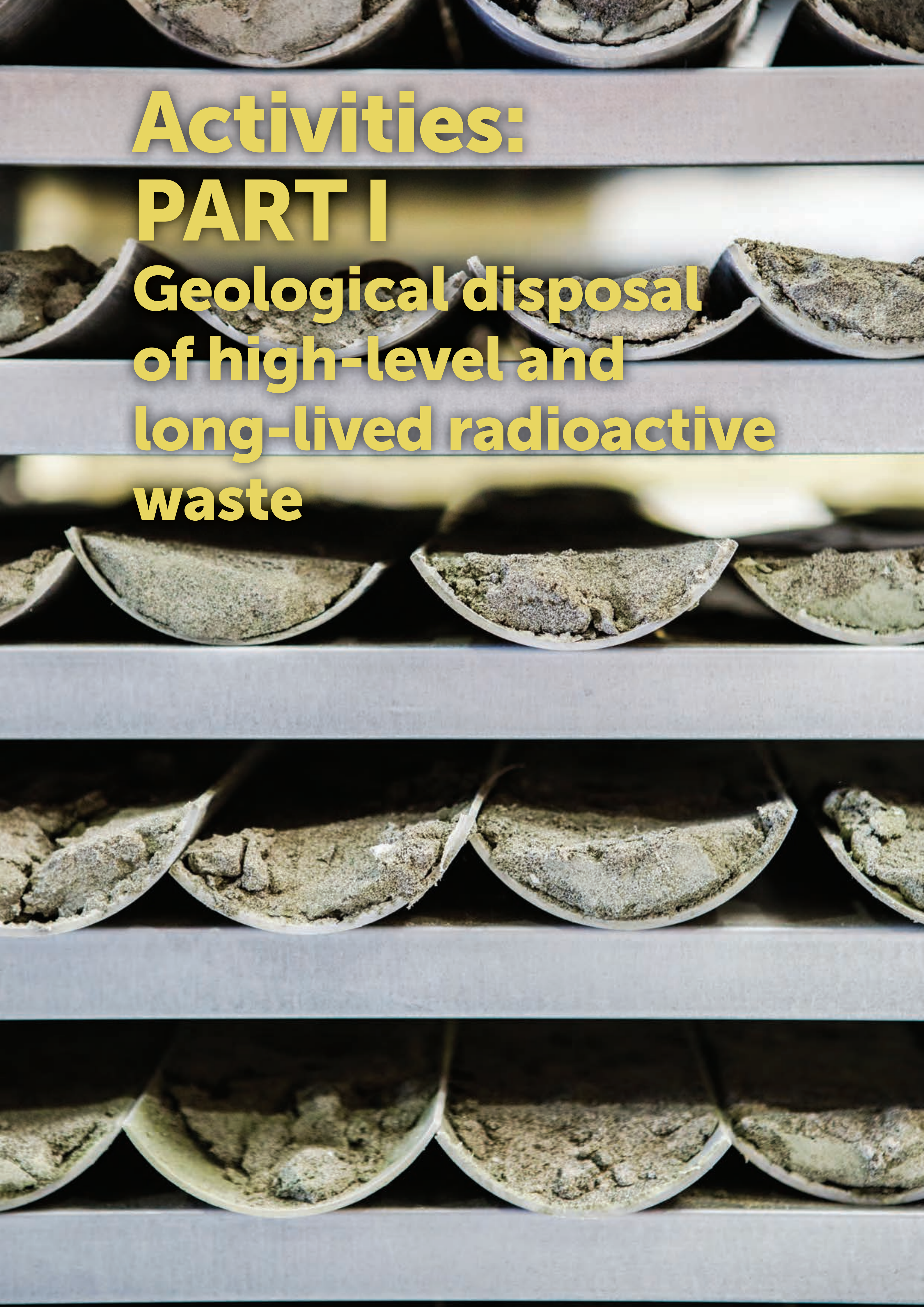
With its RD&D activities and fields of expertise, EIG EURIDICE contributes to the national programme for high-level and long-lived waste disposal managed by ONDRAF/NIRAS. In 2011 ONDRAF/NIRAS published its waste plan for the long-term management of high-level and/or long-lived waste (NIROND 2011-02, September 2011), with a view to obtaining a policy decision on the long-term management of this waste. In 2013 ONDRAF/NIRAS finalised its RD&D plan on geological disposal (NIROND-TR 2013-12 E), describing the main achievements and future challenges. The next milestones of the national programme will largely depend on the timing and nature of the policy decision.

EIG EURIDICE's scientific activities in 2017 focused on following up the PRACLAY Heater test. After a successful switch-on of the heating system on 3 November 2014, the temperature at the interface between the concrete lining and the clay reached 80°C in August 2015, marking the end of the start-up phase. Since then, the power of the heating system has been systematically adjusted to keep the temperature constant at 80°C (stationary heating phase). In 2017 a second report was prepared on the experimental evolution during the start-up phase and the first two years of the stationary phase at 80°C. This report also includes an initial evaluation of the objectives of the Heater test.

This Activity Report gives an overview of the main observations regarding the PRACLAY Heater test since switching on the heating system up until the end of 2017, based on measurements from the numerous sensors that are installed in the PRACLAY gallery, the seal, the concrete lining and in instrumented boreholes around the PRACLAY gallery. In general, the experiment is proceeding as expected. The experimental set-up has proved to be robust and the measurements in the clay are in line with the numerical predictions that were made by modelling.

Activities: PART I

Geological disposal of high-level and long-lived radioactive waste



1. PRACLAY "Demonstration & confirmation experiments"

1.1. Introduction: the PRACLAY project

One of the aims of EIG EURIDICE is the development and execution of the PRACLAY project to demonstrate the feasibility of the disposal of high-level, heat-producing vitrified radioactive waste or spent fuel in deep clay strata such as the Boom Clay.

The PRACLAY project consists of several sub-projects and experiments. Together, these are referred to as the PRACLAY "Demonstration & confirmation experiments". The aims of these experiments are:
- To demonstrate the feasibility of underground construction in the Boom Clay.
- To demonstrate the feasibility of the disposal concept for high-level waste in the Boom Clay.
- To confirm and expand knowledge about the thermo-hydro-mechanical-chemical behaviour of the Boom Clay and the gallery lining.

With the PRACLAY experiments, EIG EURIDICE is making an important contribution to the Safety and Feasibility Cases, which are part of the ONDRAF/NIRAS programme for long-term management of category B (low and/or intermediate level and long-lived) & C (high-level) radioactive waste.

In general, a distinction can be made between two groups of experiments: PRACLAY IN-SITU (meaning "in HADES") and PRACLAY ON-SURFACE experiments.

PRACLAY IN-SITU experiments can be divided into demonstration experiments and confirmation tests. The **demonstration experiments** focused on excavation techniques and construction of a shaft and galleries. The excavation of the Connecting gallery using a tunnelling machine, for example, demonstrated the feasibility of constructing galleries on an industrial scale. With the construction of the PRACLAY gallery in 2007, it was shown that it is possible to make perpendicular connections between a disposal gallery and a main gallery, making use of a reinforcement structure. Most of the PRACLAY demonstration experiments are now finished. The **confirmation tests** are focusing on confirming and improving existing knowledge about the thermo-hydro-mechanical behaviour of the Boom Clay surrounding a disposal infrastructure. The **Heater test** is the main experiment in this regard. The objective of this test is to confirm, on a large scale, that the thermal load generated by the heat-emitting waste will not jeopardise the safety functions of the host rock. In particular, the Heater test aims to assess the consequences of the coupled thermo-hydro-mechanical impact on the Boom Clay and the evolution of the excavation-damaged zone (EDZ) during the thermal transient in the case of disposal of heat-emitting waste. The status of the PRACLAY Heater test is discussed in Section 1.2.

For this purpose, part of the PRACLAY gallery (30 m) has been closed off with a seal structure and will be heated for a period of 10 years at a temperature of 80°C at the interface between the gallery lining and the clay. After the construction of the PRACLAY gallery in 2007 and the design and installation of the seal (2007-2010), installation of the heating system started in 2010 (primary heater) and was completed in 2014 (secondary heater). A detailed report about the design, preparation and installation of the PRACLAY experiment was published in 2013, upon conclusion of the installation phase of the experiment (EUR 13-129).

The heating system was switched on on 3 November 2014 to test all components of the experimental set-up, including the control systems of both the primary and secondary heating systems. After a successful test phase it was decided at the beginning of 2015 to continue heating. The target temperature of 80°C at the interface between the gallery lining and the clay was reached on 18 August 2015, marking the end of the start-up phase. A detailed report on the experimental evolution during the start-up phase was published in 2016 (EUR_PH_16_025).

Since then, the power of the heating system has been systematically adjusted to maintain the temperature at this interface constant at 80°C, marking the start of the stationary phase of the Heater test. A constant flow of data is generated by an extensive network of sensors installed in and around the PRACLAY gallery, and compared with the predictions made by modelling. A second report was written in 2017 (EUR_PH_17_043), summarising the observations from the start-up phase and the first two years of the stationary phase at 80°C. Marking the milestone of two successful years of heating at 80°C, the report includes an initial evaluation of the objectives of the PRACLAY Heater test.

PRACLAY ON-SURFACE experiments are studying different components of a disposal system and comprise laboratory tests to characterise these different components and their interaction. Many of the aspects that are studied on the surface are based on a specific disposal system design. No on-surface experiments were performed in 2017.

1.2. PRACLAY IN-SITU: the Heater test

1.2.1. Test set-up

The different parts of the PRACLAY Seal & Heater experimental set-up are shown in Figure 2. The heating system is installed in a 30-metre-long section of the PRACLAY gallery. This section is backfilled with sand, closed from the accessible part of the PRACLAY gallery by a seal structure and saturated with water.

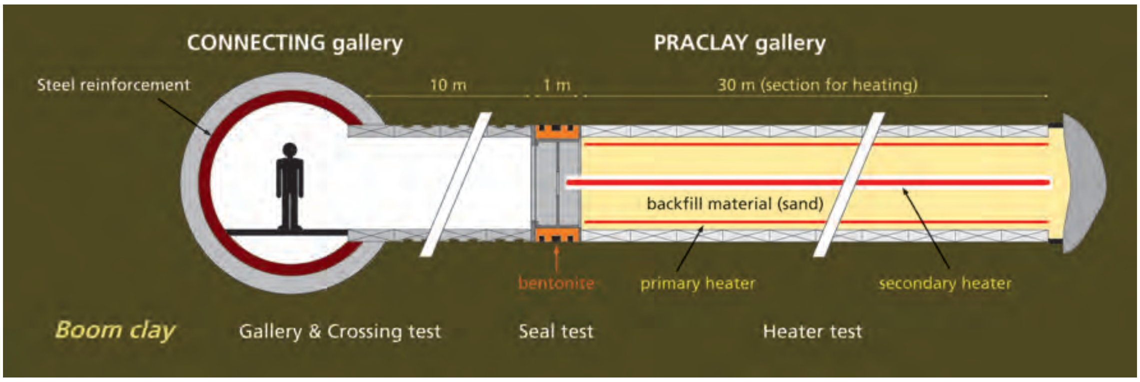


Figure 2 - Design of the PRACLAY experiment

HEATING SYSTEM
The **heating system** consists of a primary heater, attached to the gallery lining, and a secondary heater, which is placed in a central tube that rests on a support structure. Both of these are electrical heaters. Figure 3 shows the cables of the primary heater and the central tube for the secondary heater, before the gallery was closed and backfilled with sand.

Figure 3 - Cross-section of the central tube and view of the primary heating system

The **primary heater** was installed in the PRACLAY gallery in 2010. The gallery is divided into three zones (front-end, middle and far-end), each of which is subdivided into four sections (upper, lower, left, right) (Figure 4). Each section is equipped with two heater elements, ensuring 100% redundancy of the system.

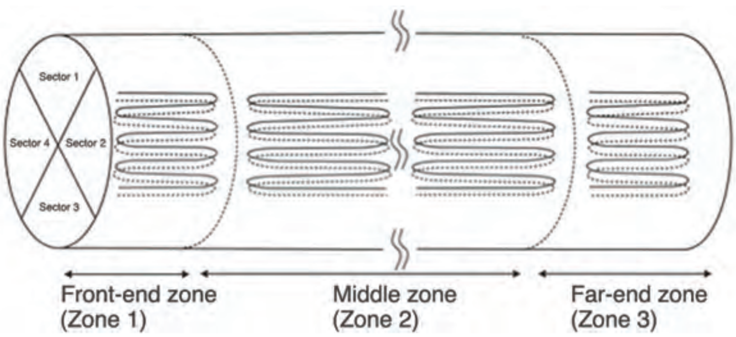


Figure 4 - The primary heating system is composed of three zones, each divided into four sections

Installation of the **secondary heater** in the PRACLAY gallery began in 2012 and was completed in 2014. It consists of eight identical secondary heater assemblies that are inserted into the central tube. For four of the assemblies, replaceability is guaranteed at all times.

A control system regulating the heating power as a function of measured and target temperature is part of the heating system. The primary and secondary heating systems each have their own control system. The primary heater is regulated in different ways for the three different zones to ensure that the temperature is kept as constant and uniform as possible (80°C at the interface between the gallery lining and the Boom Clay) over the whole heated zone during the stationary heating phase. The secondary heater can only deliver the same power output over its entire length, and this has to be regulated over time to ensure the same thermal boundary conditions (i.e. a constant temperature of 80°C at the interface between the gallery lining and the Boom Clay). The value of this power output will be set at the time of the switch-over.

HYDRAULIC SEAL

The hydraulic seal consists of a stainless steel structure closing off the heated part of the gallery from the underground infrastructure, and an annular ring of bentonite (MX80) placed against the clay (Figure 5).

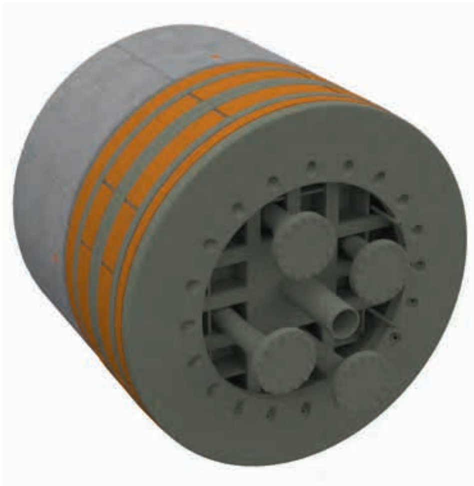


Figure 5 - 3D view of the seal with a central steel cylinder and an annular ring of bentonite (orange) against the clay

The hydraulic seal not only has to close off the PRACLAY gallery, it also has to hydraulically isolate the clay surrounding the heated part of the PRACLAY gallery, which can provide a preferential pathway for water towards the main gallery during the heating phase. Bentonite has a very low hydraulic conductivity (when compacted to a suitable dry density) and swells when it is hydrated. The swelling pressure exerted by the hydrated bentonite on the Boom Clay will lower the hydraulic conductivity of the Boom Clay around the seal, thus creating "undrained hydraulic boundary conditions" for the Heater test. The swelling behaviour of the bentonite ring in the seal is studied in the **Seal test**.

When designing the seal, two main criteria were defined. The maximum radial swelling pressure between the bentonite and the Boom Clay should be less than approx. 6.0 MPa (60 bar), so as not to re-damage the surrounding Boom Clay. The minimum swelling pressure before switch-on was set at 2.5 MPa (25 bar) to avoid creating negative effective stresses within and around the seal during the Heater test (the maximum pore water pressures in the gallery upstream of the seal and in the surrounding clay during the Heater test are estimated at 2.5 MPa by numerical prediction). The second criterion is that the hydraulic conductivity of the bentonite in saturated conditions should be lower than that of the undisturbed Boom Clay (≈ 10-12 m/s).

To meet these specifications, firstly, the initial dry density of the bentonite was carefully determined, as this parameter determines its swelling pressure and its final saturated hydraulic conductivity. The desired initial dry density was determined by scoping calculations, taking into account the technological void and the interaction with the Boom Clay. An initial dry density of 1.8 t/m^3 was selected. Secondly, the bentonite needs to be sufficiently hydrated. The bentonite seal has been hydrated since its installation in January 2010 by pore water coming from the Boom Clay and by water injected through filters placed on the outer surface (extrados) of the steel cylinder since April 2010. Different kinds of instruments were incorporated into the bentonite rings during installation to monitor the water injection rate as well as stress (swelling pressure) and pore water pressure in the bentonite and in the Boom Clay around the seal. The instruments are grouped into sections A, B and C (Figure 6).

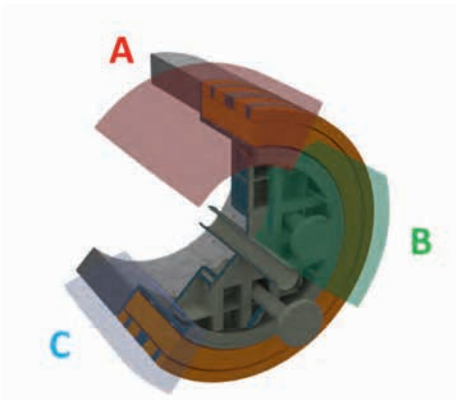


Figure 6 - Various instruments inside the bentonite, grouped into sections A, B and C

When the heating system was switched on on 3 November 2014 the radial pressures at the interface between the bentonite and the Boom Clay were around 3.3 MPa and thus higher than the required threshold value of 2.5 MPa (Figure 7). The pore water pressure in the PRACLAY backfill sand at that time had reached 1 MPa (10.0 bar) and no water leakage through the seal was observed. Hydraulic conductivity at the interface between the bentonite and the Boom Clay (at sections A, B and C) and inside the Boom Clay around the seal was measured over different periods before switch-on of the heating system and all the values obtained are similar to that of the undisturbed Boom Clay.

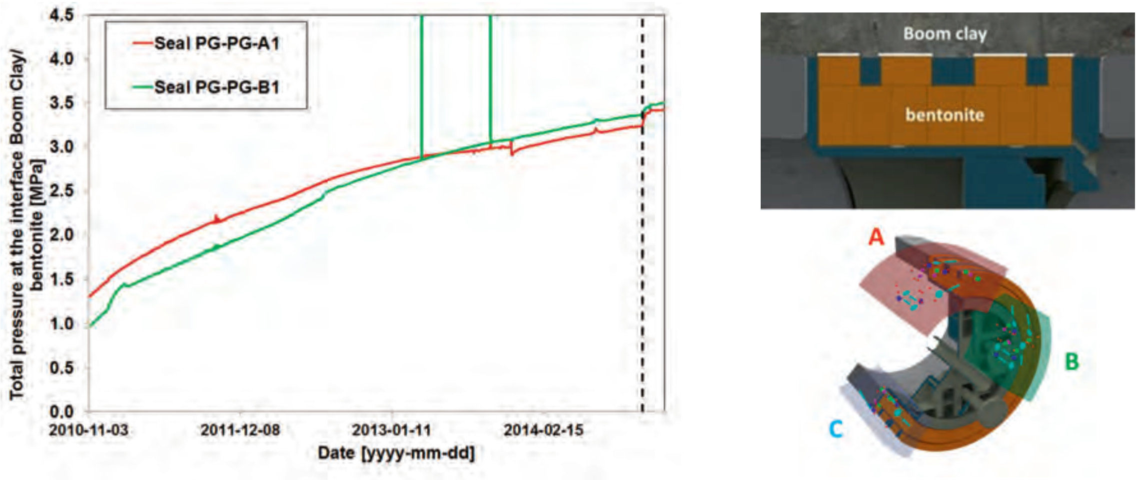


Figure 7 - Radial stresses measured at the interface between the bentonite and the Boom Clay sidewall (white line in insert), for sections A, B and C. The vertical dashed line marks the date of the switch-on.

BACKFILL SAND

The part of the PRACLAY gallery that is being heated is filled with sand (Mol sand M34) and saturated with water. The **water-saturated backfill sand** has to ensure efficient heat transfer from the heating elements to the surrounding clay and, together with the hydraulic seal, create homogeneous "undrained hydraulic boundary conditions" along the interface between the clay and the gallery lining. On 3 November 2014 the water pressure inside the gallery reached 1 MPa, and the PRACLAY gallery was estimated to be fully saturated.

MONITORING, INSTRUMENTATION AND DATA MANAGEMENT

The PRACLAY Seal and Heater tests are extensively instrumented to control the heating process and for the purpose of the experimental follow-up. To ensure convenient access to the sensor data, a user interface has been built into the database. This interface has several functionalities: a “dashboard” to give a quick overview of selected variables, the generation of a daily Safety Report, and an extensive graphical module to generate both time evolution and spatial profiles of measured variables.

INSULATION DOOR
On 2 March 2015, about four months after heater switch-on, an insulation door was installed in front of the seal (at a distance of about 1.5 m from the seal) to limit the cooling of the steel cylinder that closes off the heated section of the gallery and thereby limit the end effect of the Heater test. It also provides an operational safety barrier. The door consists of an aluminium structure that is bolted against the lining, supporting a window to allow visual inspection of the seal.

1.2.2. CONTROL, FOLLOW-UP AND MANAGEMENT OF THE HEATER TEST

MANAGEMENT GUIDE
A management guide with a set of procedures was compiled in close collaboration with ONDRAF/NIRAS in 2014 to specify the follow-up of the test, define the action plan in case of unexpected events and clearly outline and assign the different responsibilities with respect to safety, scientific objectives and technical aspects, such as maintenance and checks. The management guide was completely reviewed and updated in 2016.

NUMERICAL MODELLING
Numerical modelling plays an important role in the PRACLAY Heater test both in terms of preparation of the test and as regards controlling and interpreting it.

Prior to the switch-on of the heating system, with a view to increasing the reliability of the numerical modelling of the expected evolution of the Heater test, significant efforts were devoted to understanding and then numerically reproducing past in-situ measurements. This exercise resulted in a set of reliable parameters that were used in predictive modelling of the PRACLAY Heater test, the so-called "numerical predictions" that give an indication of how the Heater test is expected to evolve. Subsequently, different altered scenarios (i.e. deviating from the expected evolution) were studied numerically:
- To support in different ways the design and control of the various components (e.g. primary heater, secondary heater and thermal insulation door) of the PRACLAY Heater test.
- To obtain a possible range of experimental evolutions based on extensive parametric sensitivity analysis.
- To provide a clear basis for developing the procedures for the follow-up and/or management of the Heater test in the event of failure of the primary heater and/or in the event of seal or lining instability.

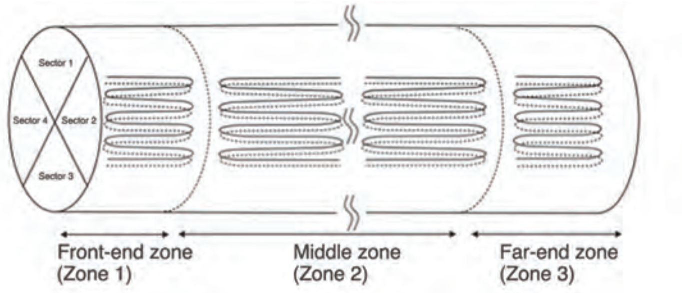
Since switch-on of the heating system, numerical modelling has received constant attention:
- to determine the primary heater power for the manual input in the heater control system during the stationary phase;
- to improve the interpretation and understanding of the measurements and observations of the Heater test.

1.2.3 OBSERVATIONS SINCE THE SWITCH-ON UNTIL THE END OF 2017

Control of the Heater test is mainly based on the temperature evolution at the interface between the concrete lining and the Boom Clay with the objective of having a temperature profile that is as uniform as possible along the 30 m long heated part of the PRACLAY gallery.

In order to ensure better control of the Heater test with respect to a uniform target temperature of 80°C, intensive modelling taking into account the end effects and also the capacity of the heating system was performed to determine the heating strategy throughout the entire experiment. In the end, it was decided to control Zone 2 and Zone 3 using two different temperature indicators. Indicator 1 (T_{int_1}) is the average temperature measured at the outer surface of the liner in Zone 2 using the thermocouples embedded in the concrete liner in rings R37, R50 and R55. Indicator 2 (T_{int_2}) uses the average temperature measured by the sensors at the extrados of Ring 81 to control the temperature in Zone 3 (Figure 8 and Figure 9). It was also decided that the power for Zone 1 would mirror that for Zone 2 in spite of the end effect of heat dissipation so as to avoid overheating of the seal structure (safety precaution).

The power and associated temperature evolution in the three zones are illustrated in Figure 8 and Figure 9. In order to attain the target temperature of 80°C, the power in the three zones of the primary heating system was increased stepwise. As expected, the target temperature in Zone 2 (measured by T_{int_1}) was reached first in mid-August 2015; the power in Zone 2 (and therefore in Zone 1) was decreased accordingly to keep this target temperature constant. The beginning of this power decrease was considered to be the start of the stationary phase. Once the target temperature in Zone 3 (measured by T_{int_2}) was reached in early June 2016, the power in this zone was decreased accordingly to keep it constant.



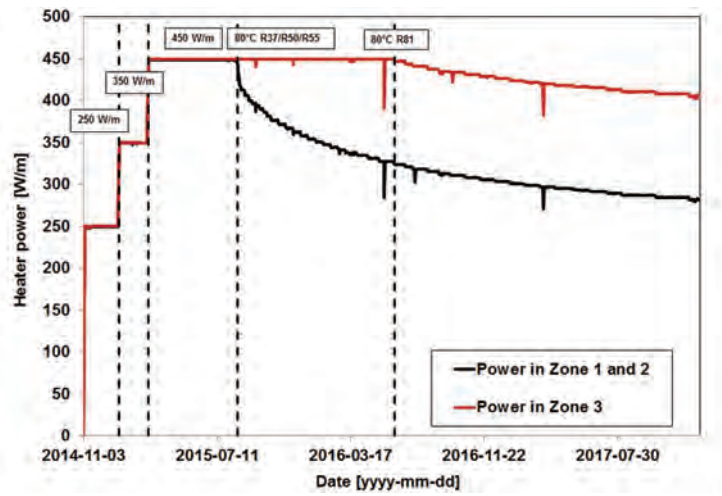


Figure 8 - Evolution of the power in watts per metre (W/m) in the three zones. The power in Zones 1 and 2 was decreased once the temperature in Zone 2 reached 80°C (measured by T_{int_1}). The power in Zone 3 was decreased with a delay of a couple of months once Zone 3 reached 80°C (measured by T_{int_2}).

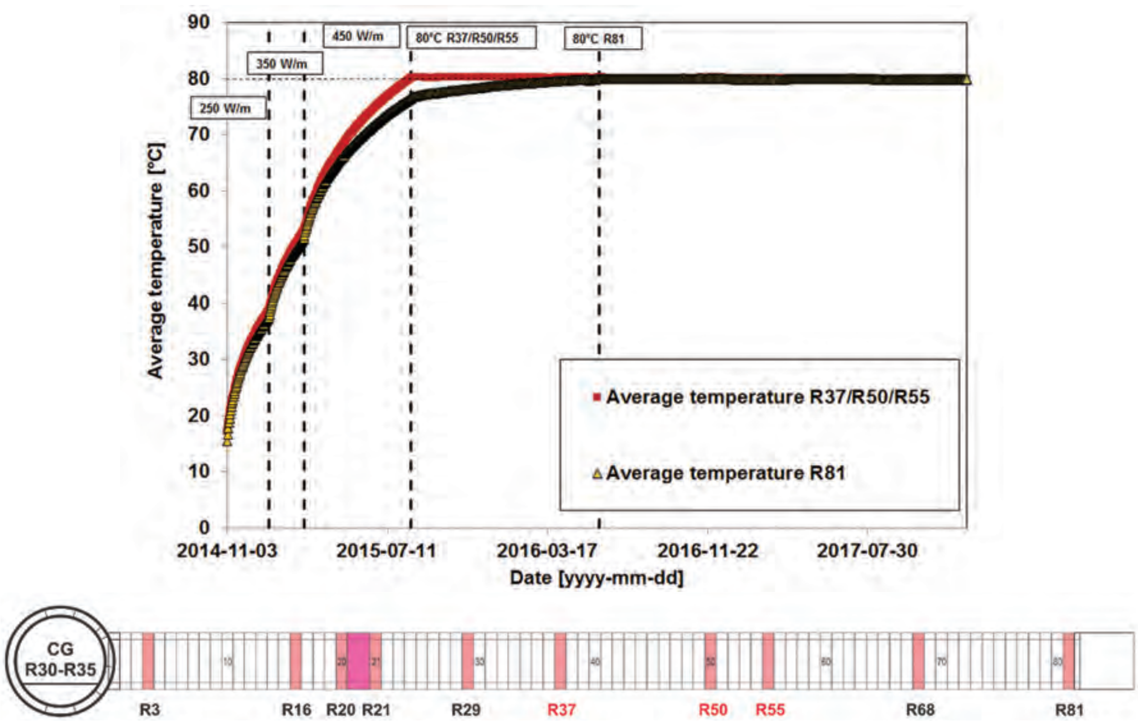


Figure 9 - Average temperature evolution measured using the extrados sensors in R37, R50 and R55 (T_{int_1}) and R81 (T_{int_2})

This heating strategy made it possible to obtain a reasonably homogenous temperature distribution at the extrados of the lining along the heated part of the gallery, as illustrated in Figure 10, though with some heterogeneities. This means that the target temperature of 80°C might be reached at some specific locations, while the rest might be slightly below or above this target temperature. This is one of the reasons that an "average" temperature over the selected thermocouple sensors at the extrados of lining rings was used as the temperature indicator for controlling the experiment.

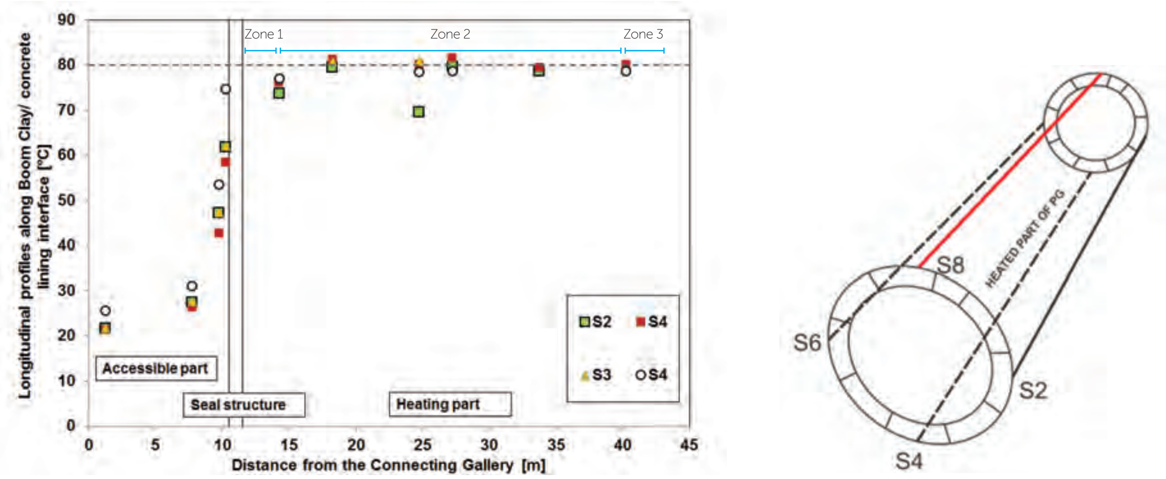


Figure 10 - Longitudinal profiles of the temperature along the extrados of the PRACLAY gallery (end 2017)

Following heating and due to the difference in the thermal dilatation coefficient between the solid and the fluid part of the water-saturated sand and the overall hydro-mechanical constraints applied by the surrounding materials (low permeability and relative higher rigidity of the liner and the Boom Clay), an excess pore water pressure of the system is induced inside the PRACLAY gallery. This rise in pore water pressure in the backfilled part of the PRACLAY gallery is shown in Figure 11. During the start-up phase of the Heater test, the pore water pressure rose quickly at the beginning of each heating step, followed by a more gradual increase, due to progressive dissipation of water pressure in the surrounding clay. After the target temperature was reached in Zone 2 in August 2015, the pore water pressure fell briefly then levelled off. It is noted that, due to the fairly high hydraulic conductivity of the backfill material, the pore water pressure inside the backfilled part of the PRACLAY gallery is quite uniform.

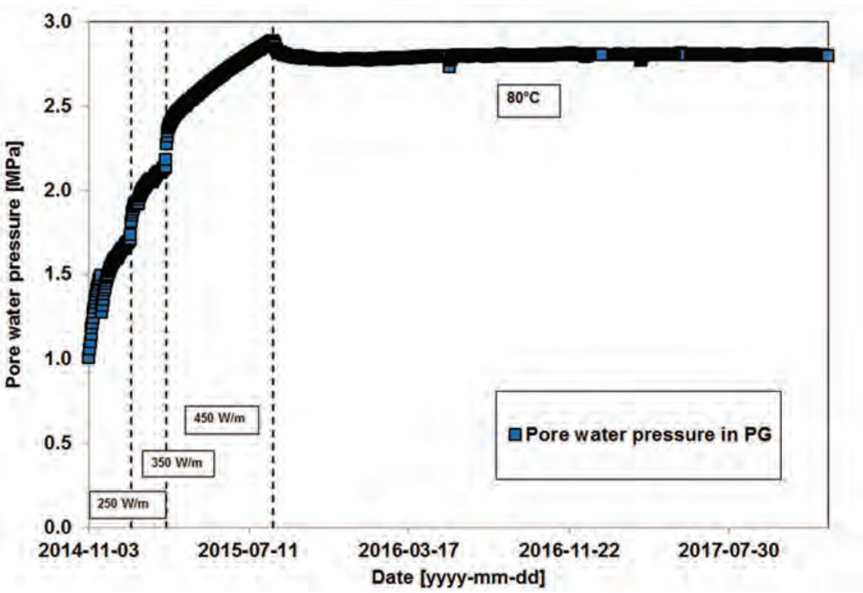


Figure 11 - Pore water pressure evolution in the backfilled part of the PRACLAY gallery

BOOM CLAY RESPONSES

Sediments with low permeability, like the Boom Clay, can experience a substantial increase in pore water pressure as a consequence of a temperature rise due to the differential thermal dilatation coefficient between the solid (skeleton) and the liquid phase (mainly water) in the clay (thermo-hydro-mechanical coupling behaviour). The variation in the temperature and pore water pressure inside the Boom Clay is monitored using instrumented boreholes extending in different directions from the PRACLAY gallery and from the Connecting gallery (Figure 12).

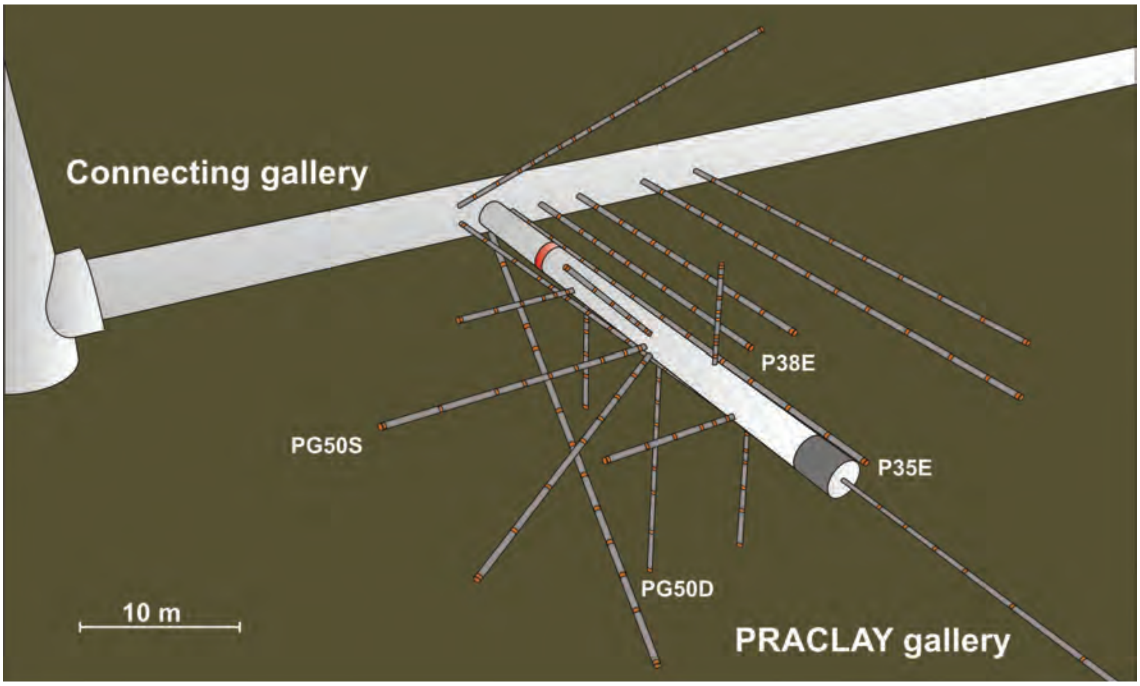
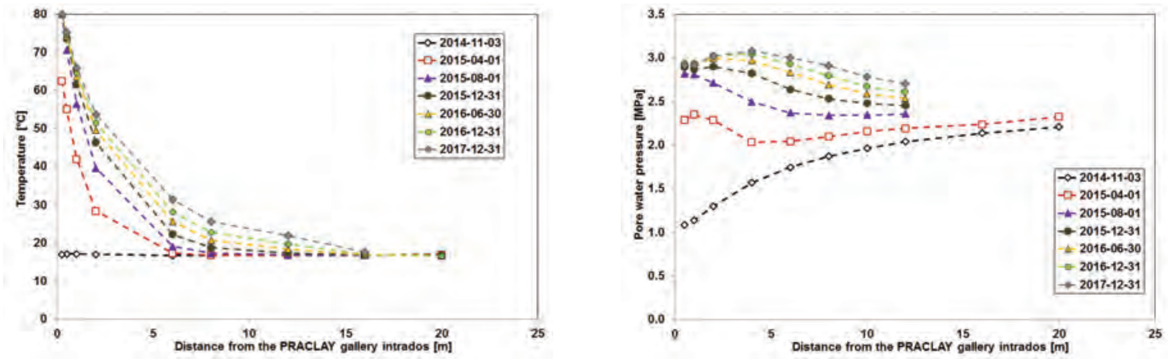


Figure 12 - 3D view of the instrumented boreholes from the PRACLAY gallery and the Connecting gallery

The evolution of the temperature and pore water pressure profiles in the vertical direction (monitored from the downward borehole PG50D in the middle section of the heated gallery) is shown in Figure 13. The evolution of the temperature and pore water pressure profiles in the horizontal direction (measured from the boreholes, drilled from the Connecting gallery and parallel to the PRACLAY gallery, with the sensors located at the middle section of the heated gallery, as shown in Figure 12) is shown in Figure 14.

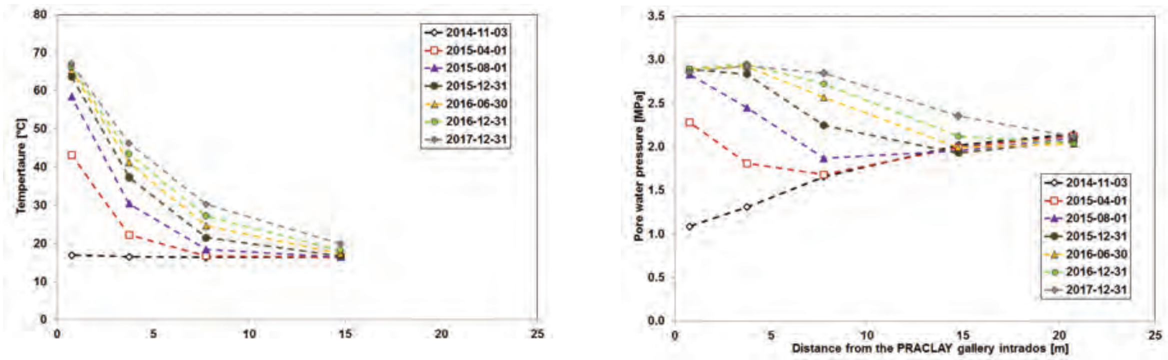
It was observed that, at the end of 2017, the thermally affected zone had extended to a depth of about 15 m into the Boom Clay in the vertical direction (Figure 13a), and probably more than 15 m into the Boom Clay in the horizontal direction (Figure 14a). At a given time and at the same distance from the heater, the temperature rise in the horizontal direction is larger than that in the vertical direction. These observations clearly indicate an anisotropic heat transfer mechanism through the Boom Clay, as already observed in small-scale in-situ heater tests.

Concerning the evolution of the pore water pressure, close to the lining, the pore water pressure increased as expected from its initial value of 1 MPa before heating to a value close to 3 MPa at the end of the start-up phase (August 2015). Since the beginning of the stationary phase, the pore water pressure has remained nearly constant close to the lining but continues to increase in the clay. Over time the peak in pore water pressure has gradually shifted away from the gallery into the Boom Clay (Figure 13b and Figure 14b).



(a) (b)

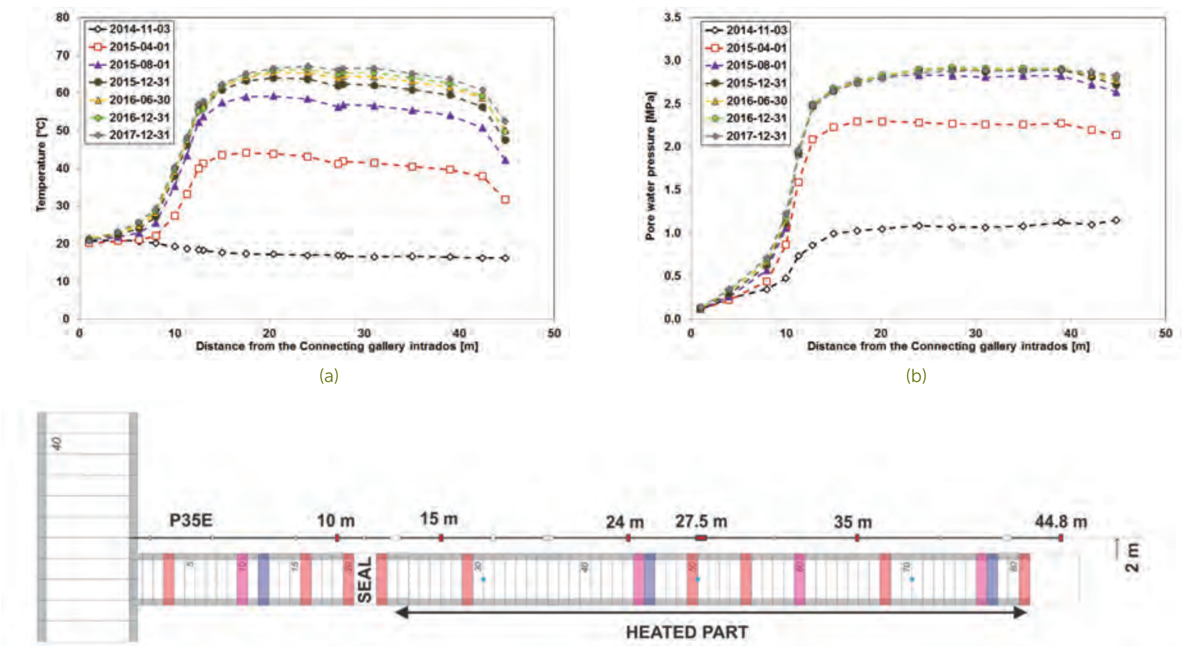
Figure 13 - Temperature and pore water pressure profiles in the vertical direction at the middle section of the heated part of the PRACLAY gallery (along borehole PG50D)



(a) (b)

Figure 14 - Temperature and pore water pressure profiles in the horizontal direction at the middle section of the heated part of the PRACLAY gallery (measured from boreholes drilled from the Connecting gallery)

Spatial distribution of the temperature and pore water pressure around the PRACLAY gallery is illustrated in Figure 15 and Figure 16. Figure 15 shows the temperature and pore water pressure profiles along P35E, located approximately 0.75 m from the extrados of the gallery lining. The pore water pressure profile is almost uniform along P35E (Figure 15b), while the temperature profile shows a slight gradient from the seal to the end part of the PRACLAY gallery (Figure 15a). The pore water pressure profile in Figure 15b clearly shows the hydraulic cut-off by the seal.

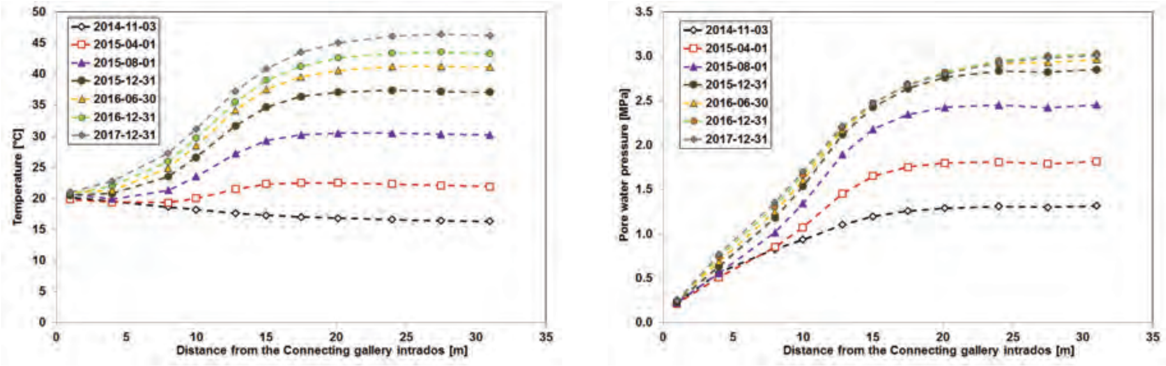


(a) (b)

(c)

Figure 15 - Temperature and pore water pressure profiles in P35E

The temperature and pore water pressure at a distance of 5 m from the axis of the PRACLAY gallery (measured by the sensors in borehole P38E; see Figure 12) can be seen in Figure 16. The pressure in this borehole reached almost 2.8 MPa in the deepest part of the borehole, which is also closest to that inside the PRACLAY gallery. Overall, the pore water pressure measured by these sensors remained very stable and rose only very slightly during 2017.



(a) (b)

Figure 16 - Temperature and pore water pressure profiles in P38E

EVOLUTION OF THE HYDRAULIC SEAL

The hydration of the bentonite and the associated pore water pressure and total pressure evolution were continuously monitored during the heating phase. Figure 17, for example, shows the evolution of the pore water pressure at the Boom Clay/bentonite interface with the different heating steps. It can be observed that the pore water pressure at the Boom Clay/bentonite interface evolves in the same way for the three sections A, B and C. One of the main purposes of the seal structure is to provide a hydraulic cut-off between the heated and the non-heated part of the experiment. The effect can be observed in the different evolution of the pore water pressure in sensors Seal-PP-A1 and Seal-PP-A3 in section A. The first is located close to the heated part, while the second is close to the accessible, non-heated part of the PRACLAY gallery. A significant difference of nearly 1 MPa over a distance of only 34 cm between both sensors can be observed, indicating that the seal is functioning well. Moreover, the pore water pressure inside the PRACLAY gallery is maintained as expected due to the seal performing well.

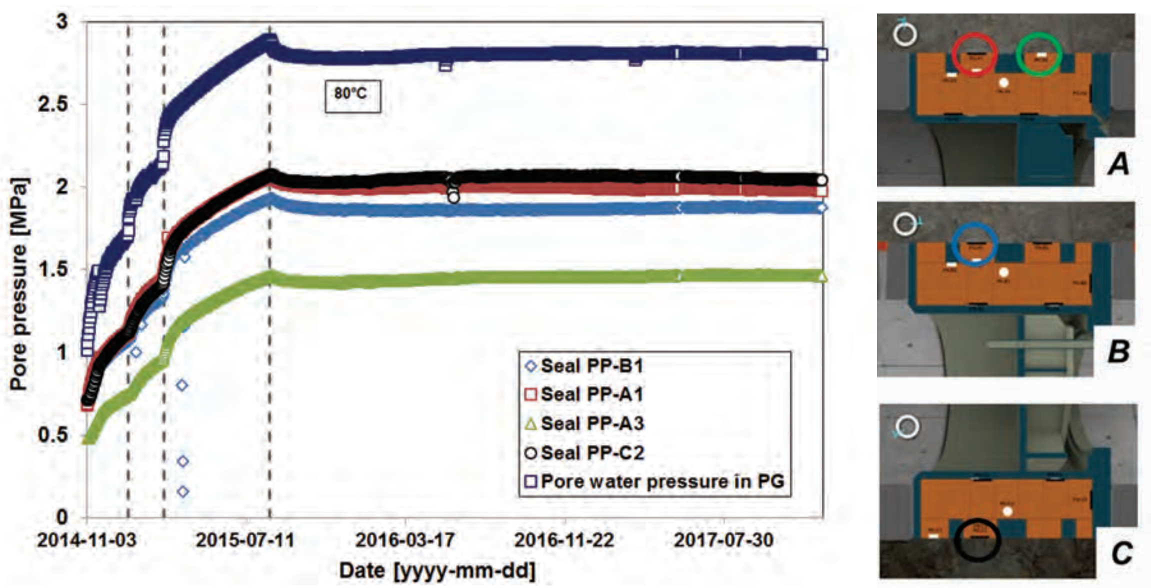


Figure 17 - Evolution of the pore water pressure at the Boom Clay/bentonite interface

In order to highlight the effect of the seal, Figure 18 shows the evolution of the pore water pressure at the Boom Clay/bentonite interface for different positions in section A, and at the Boom Clay/concrete lining interface close to section A. It is worth noting that between the non-heated and heated parts of the gallery, a big difference in pore water pressure of almost 2 MPa occurs over a distance of 1.5 m. This significant gradient is clear proof of the good hydraulic cut-off created by the seal: the high pressure inside the backfilled part of the gallery was maintained.

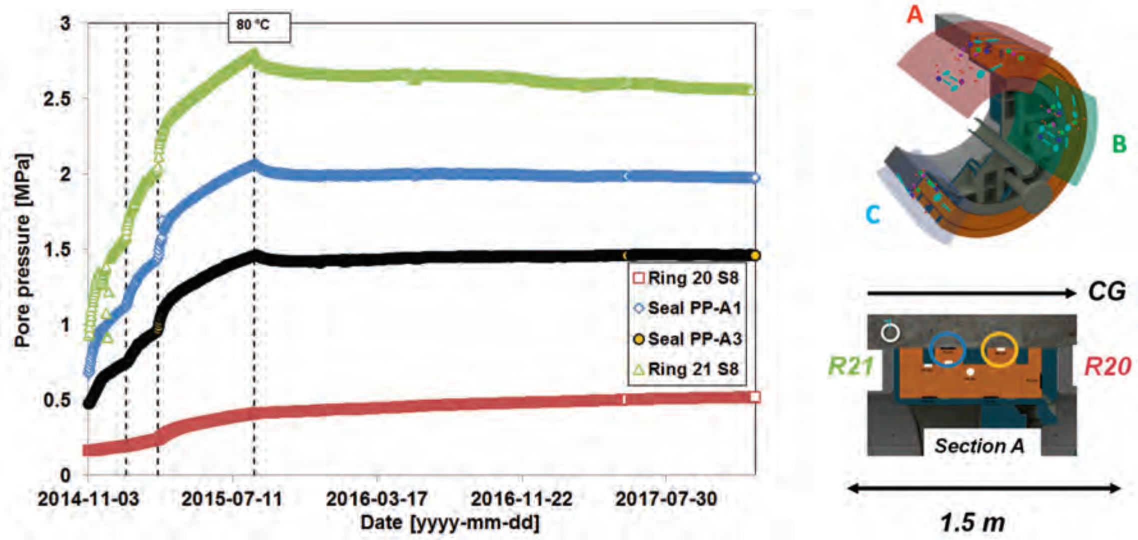


Figure 18 - Pore water pressure evolution at the Boom Clay/concrete lining and Boom Clay/bentonite interfaces

The evolution of the total pressure at the Boom Clay/bentonite interface can be seen in Figure 19. A slow increase is observed during the start-up heating phase. This increase seems to be steady. A variation in total pressure of about 1 MPa has been observed since heating was first applied, indicating a slow hydration and swelling process. Compared with the beginning of the second heating step, the relatively faster increase in total pressure at the beginning of the third heating step is mainly linked to the installation of the thermal insulation door in front of the seal, which temporarily caused a rapid increase in temperature. Indeed, the purpose of the door is to limit the heat loss in the accessible part of the PRACLAY gallery. As a consequence, the temperature of the seal increased and the total pressure at the Boom Clay/bentonite interface rose slightly.

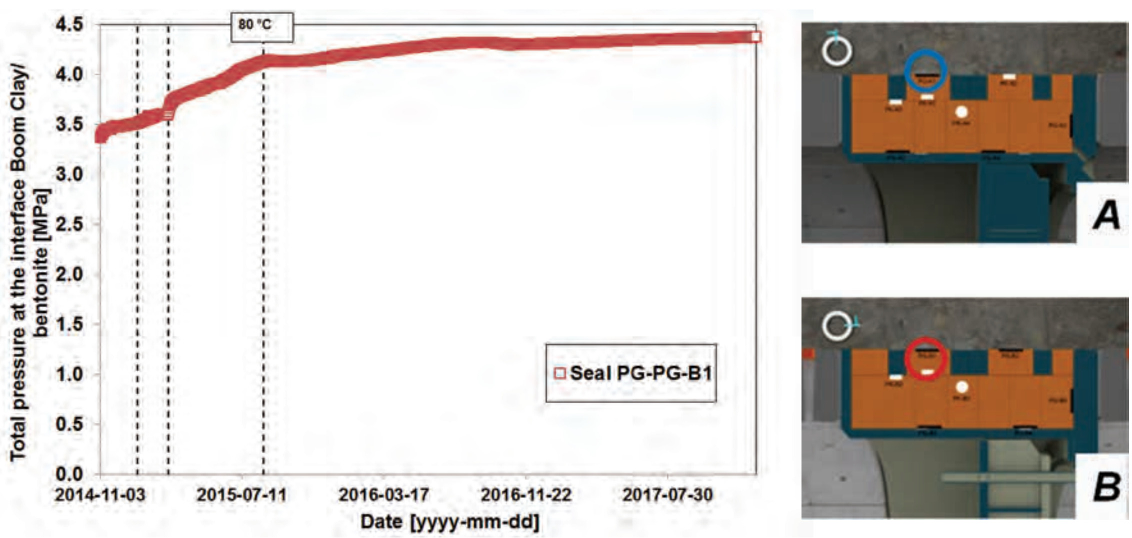


Figure 19 - Total pressure at the Boom Clay/bentonite interface in sections A and B

The movement of the seal structure towards the Connecting gallery was monitored by a total station and prisms attached to this structure, as can be seen in Figure 20. A significant increase in displacement during the start-up phase can be observed, but this has tended to be steady since the beginning of the stationary phase. An average displacement of 12 mm was observed at the end of 2017, without any impact on the stability and the functioning of this seal structure.

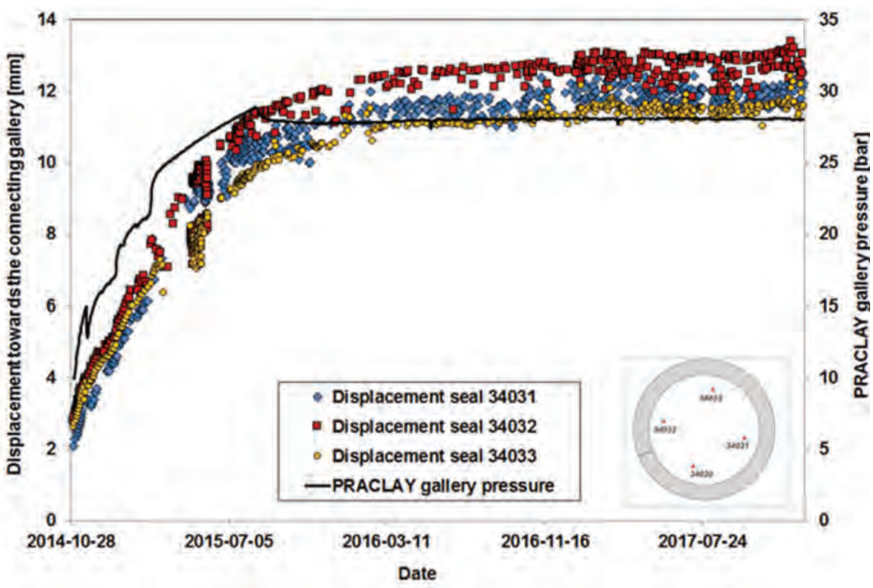
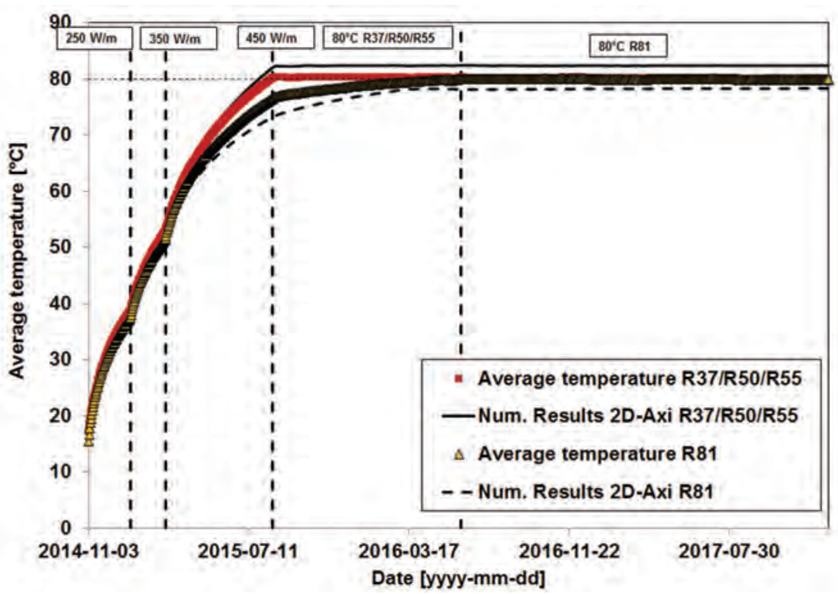


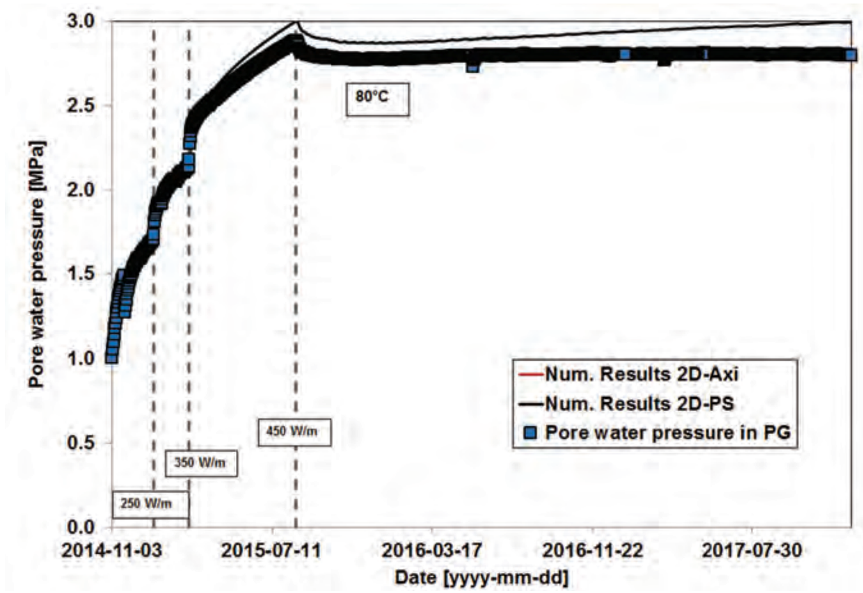
Figure 20 – Evolution of the movement of the seal structure towards the Connecting gallery since the beginning of the heating phase

COMPARISON BETWEEN MEASUREMENTS AND NUMERICAL PREDICTIONS

As already mentioned, intensive predictive modelling was performed before the start of the experiment and during the heating phase. The aim of this work was to enable a comparison to be made between the experimental measurements and the so-called "numerical predictions" from the modelling, and to detect any deviations in the experimental results from these predictions. Figure 21 shows the evolution of the temperature at the interface of the lining and the Boom Clay and pore water pressure in the backfilled part of the PRACLAY gallery compared with the modelling results. Good agreement can be observed for both parameters. Figure 22 indicates the evolution of the temperature and pore water pressure inside the Boom Clay compared with the numerical modelling results. Regarding temperature, it can be stated that, in general, the numerical predictions correspond well with the actual (i.e. measured) evolution of the temperature inside all the components of the experiment (Figure 21a and Figure 22a). The pore water pressure evolution inside the Boom Clay can also be modelled, but with a different level of agreement depending on the distance from the PRACLAY gallery (Figure 22b).

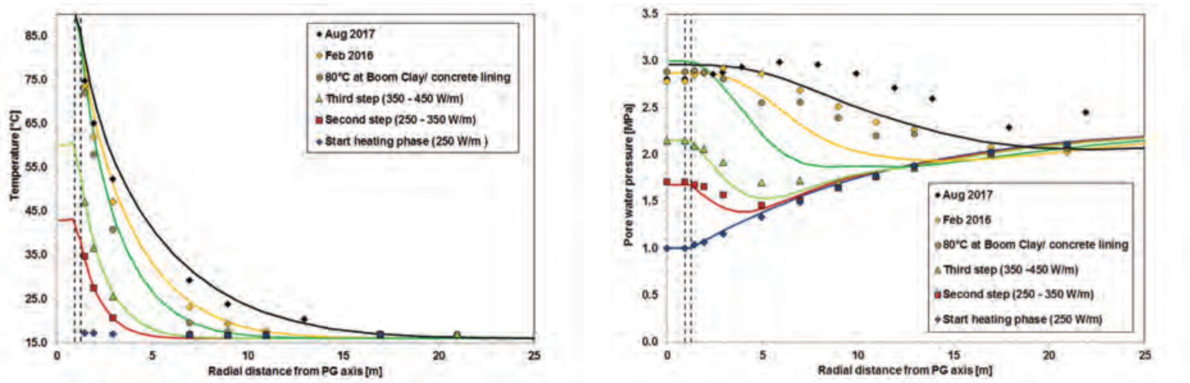


(a)



(b)

Figure 21 - Evolution of the temperature at the extrados of the lining and pore water pressure inside the PRACLAY gallery, compared with the numerical predictions



(a) (b)

Figure 22 - Comparison between the measured and modelled temperature and pore water pressure (horizontal profiles)

PERMEABILITY TESTS AROUND THE CONNECTING GALLERY AND PRACLAY GALLERY

In order to study the excavation-induced permeability variation and subsequent self-sealing behaviour of the Boom Clay, systematic permeability tests were conducted in HADES. Moreover, around the PRACLAY gallery, permeability tests were carried out on the selected filters before and during the heating phase, with the main objective being to check the effect of heating on Boom Clay permeability and self-sealing behaviour.

In 2017 in-situ permeability tests were performed on two groups of filters (Group 1 and Group 2) in boreholes CG35E, CG38E, CG42E, CG49E and CG55E (see Figure 23). Group 1 contains the filters located at a distance of 24 m from the Connecting gallery intrados, and Group 2 the filters at a distance of between 31 and 32 m. These two groups of filters are close to the mid-plane of the heated part of the PRACLAY gallery and almost symmetrical to that mid-plane. The new test results were compared with those obtained before the Heater test (Figure 24a). Taking into account the temperature dependence of water viscosity, the calculated intrinsic permeability is shown in Figure 24b.

A comparison of the test results before and after switch-on of the heating system indicates that, even on a large scale, the increase in hydraulic conductivity of the Boom Clay with an increase in temperature is mainly due to the decrease in liquid viscosity. This means that no significant change in the intrinsic permeability with temperature can be noted. This confirms the laboratory investigations on the Boom Clay and also the results from the smaller-scale in-situ ATLAS heating tests.

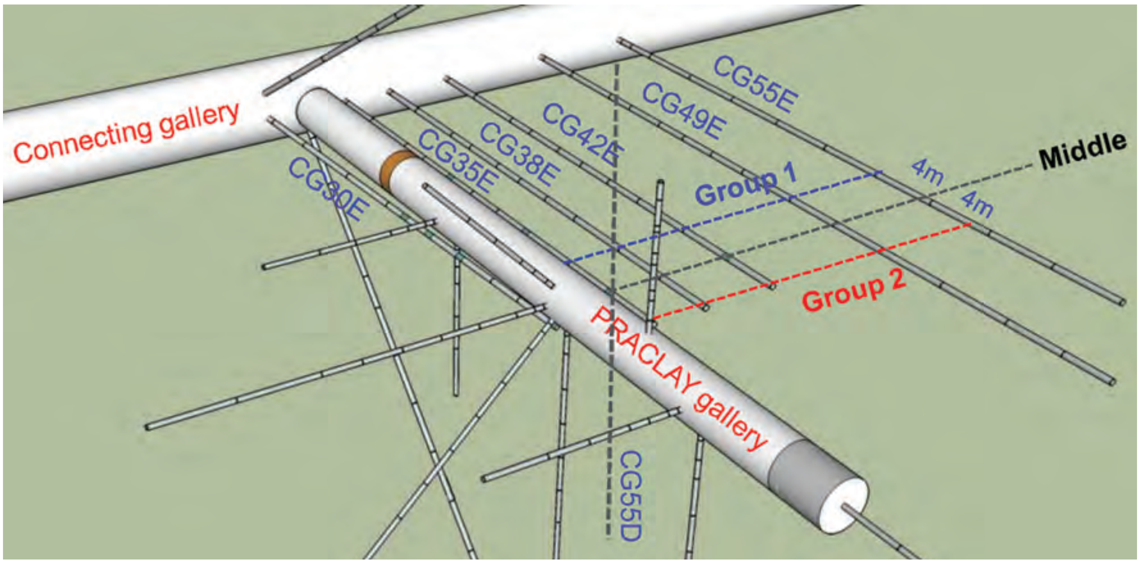


Figure 23 - Two filter groups selected from CG boreholes CG35E, CG38E, CG42E, CG49E and CG55E

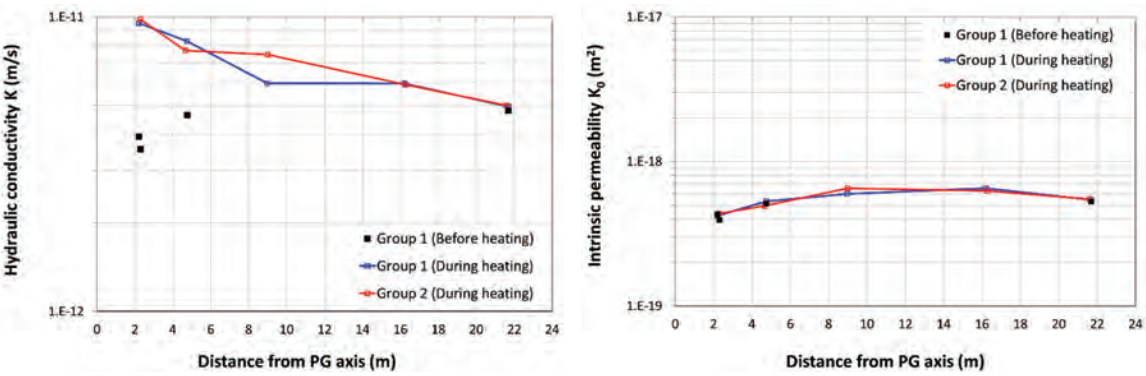


Figure 24 - Hydraulic conductivity (left) and intrinsic permeability (right) measured on the two groups of filters before and during heating

In addition, to get a complete picture of the permeability distribution around the PRACLAY gallery on a larger scale, the opportunity was taken to measure the in-situ permeability with the filters above and below the PRACLAY gallery where the temperature is merely affected by heating. The measured permeability values correspond well with the detailed lithostratigraphy of the Boom Clay formation, as derived from the Formation Micro Imager (FMI) in the Mol-1 borehole.

A report entitled "In-situ hydraulic conductivity measurement in the Boom Clay around the Connecting gallery and the PRACLAY gallery" will be available early in 2018.

1.2.4 IMPROVED INTERPRETATION OF THE TEST RESULTS BY MODELLING

A different level of agreement was observed between the predictive numerical modelling and the in-situ measurements of temperature and pore water pressure in the test components (Figure 21 and Figure 22). In order to be able to interpret and reproduce the test results more accurately, a great deal of effort was expended in 2017 to improve the models and refine the THM parameters step by step.

IMPROVED INTERPRETATION OF THE MEASURED TEMPERATURE

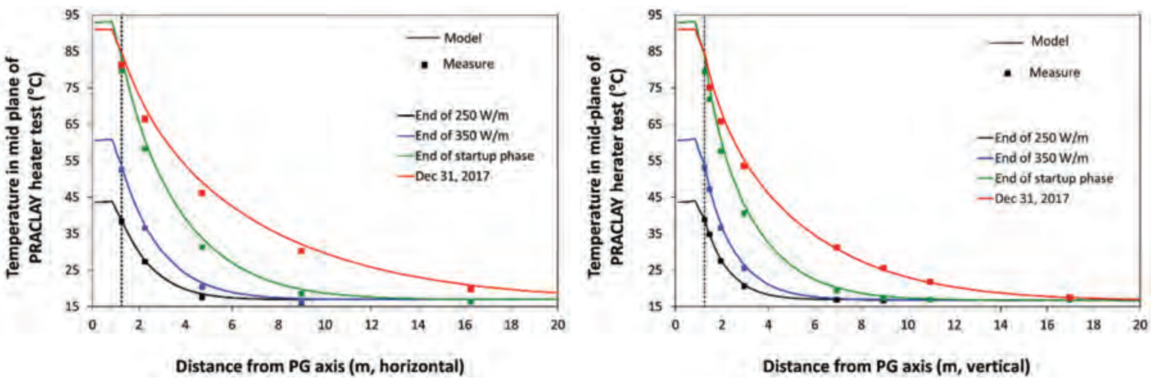
The temperature variation in the Boom Clay is dominated by heat conduction. Since the hydro-mechanical coupling effect on heat transfer can be ignored, the first step in improving interpretation focuses on the three-dimensional thermal problem without hydro-mechanical coupling. For this purpose, a **three-dimensional numerical model** was developed, which was an improved model to interpret the temperature compared with the two-dimensional predictive models. This 3D model took into account both the thermal anisotropy and the actual test geometry, especially in the Connecting gallery.

Meanwhile, in order to speed up interpretation and also to cross-check the theoretical soundness of the numerical modelling, an **approximate three-dimensional analytical solution** to calculate the temperature was developed, which, at the actual phase of the development, has proven to be very helpful and efficient for the determination of the anisotropic ratio of the thermal conductivity of the Boom Clay based on the in-situ measured data from the PRACLAY Heater test.

Benefiting from the above two models, an improved pair of thermal conductivity parameters was obtained, and the temperature measured around the mid-plane of the PRACLAY Heater test was accurately reproduced in both horizontal and vertical directions (see Figure 25).

A small-scale in-situ ATLAS IV heating test was carried out in HADES in 2011-2012. To verify the pair of thermal conductivity parameters obtained from the PRACLAY Heater test, they were used to model the ATLAS IV heating tests. A comparison of the temperature at five representative points between the measurement and the modelling was made, and excellent agreement can be observed, as shown in Figure 26.

Although good agreement of the temperature between modelling and measurement at most temperature sensors was obtained for the PRACLAY Heater test and ATLAS IV heating test, the different degree of deviation still exists at some sensors. Once all the sensor coordinates and the actual heater power have been double-checked, an inverse analysis of all the temperature measurements in both the PRACLAY Heater test and the ATLAS IV heating test will be carried out in 2018 to further refine the thermal parameters.



(a) Horizontal direction

(b) Vertical direction

Figure 25 - Comparison of the temperature between modelling and measurement in the mid-plane of the PRACLAY Heater test

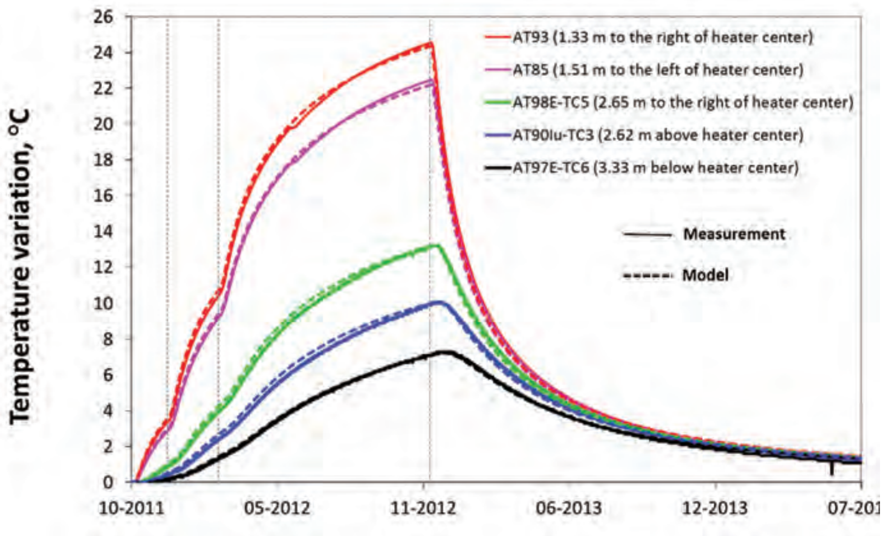


Figure 26 - Comparison of the temperature between modelling and measurement for five representative sensors in the ATLAS IV heating test

IMPROVED INTERPRETATION OF THE MEASURED PORE PRESSURE

The pore water pressure evolution depends heavily on the thermo-hydro-mechanical coupling behaviour. As the 3D coupled THM model is very time-consuming due to the scale and complexity of the problem, at this stage improvement of the interpretation of the pore water pressure evolution is still based on a 2D axisymmetric THM model.

In 2017, in parallel with the three-dimensional analysis of the above-mentioned thermal problem, some modelling work was carried out with the aim of better interpreting and understanding the pore water pressure evolution, for example:

- The mechanical model for the Boom Clay was improved by defining Young's modulus as a function of the equivalent von Mises strain, which takes better account of the excavation-induced damage in terms of mechanical properties compared with the numerical prediction.
- Detailed analysis of all existing data on the permeability of the Boom Clay revealed that the permeability of the Boom Clay measured in situ around the Connecting gallery and PRACLAY gallery is systematically higher than that measured in the laboratory. To investigate the influence of this different Boom Clay permeability on the pore water pressure evolution around the PRACLAY gallery, additional sensitivity analysis was performed using numerical modelling with the objective of refining the HM parameters of the Boom Clay.
- The dependence of the thermal expansion coefficient on temperature is well known for pure water, but it is not so evident for pore liquid in clay. To gain insight into its influence on the pore water pressure evolution in the Boom Clay, a numerical sensitivity analysis was carried out, which indicated that the thermal expansion coefficient of the pore liquid has a significant influence on the thermally induced pore water pressure. Consequently, it was concluded that further investigation of this issue would be helpful to improve the interpretation of the measured pore water pressure evolution around the PRACLAY gallery.

Once again, to gain more confidence in the interpretation results, the numerical modelling for the small-scale ATLAS IV heating test was performed to validate the improved models and the refined THM parameters resulting from the interpretation of the PRACLAY Heater test.

Due to the complexity of the coupled THM processes, the interpretation of the pore water pressure using the two-dimensional axisymmetric coupled THM model is still ongoing.

1.2.5 INSTALLATION OF NEW BOREHOLE CG62E

In 2017 the installation of an additional instrumented borehole as part of the PRACLAY Heater test was discussed and prepared. With the existing instrumented boreholes, the temperature and pore water pressure in the Boom Clay can be measured to a horizontal distance of 16 m and 22 m, respectively, from the PRACLAY gallery. However, numerical modelling predicted that after the 10-year heating phase the thermally affected zone would be more than 30 m and the hydraulically affected zone would extend more than 40 m. With the successful running of the experiment it was decided to extend the monitored temperature and pore pressure field from the PRACLAY Heater test, with the installation of a new borehole at a horizontal distance of 29 m from PRACLAY gallery. This borehole will be drilled from the Connecting gallery and instrumented with thermocouples, pore water pressure sensors and total pressure sensors. All components were manufactured and purchased in 2017. Installation of this instrumented borehole is planned for January 2018.

1.2.6 PRELIMINARY ASSESSMENT OF THE PRACLAY HEATER TEST OBJECTIVES

A second follow-up report was written in 2017, focusing on the evolution of the PRACLAY Heater test during the start-up phase and the first two years of the stationary phase. At the same time, an initial preliminary assessment of the Heater test objectives was made, based on the observations and on the comparisons with the numerical predictions. At this stage of the experiment, it is worth pointing out that the whole experimental set-up works as expected, indicating early success in this experiment after nearly three years of heating:

1. The heating system continues to deliver the correct amount of power needed to control the experiment.

2. The seal structure has demonstrated its ability to sustain the high pressure inside the PRACLAY gallery and continues to fulfil its role as hydraulic cut-off in ensuring quasi-undrained boundary conditions for the Heater test.

3. In terms of the monitoring programme, even though a number of sensors failed or delivered data with artefacts, the overall follow-up and control of the experiment were not jeopardised, thanks to the extensive network of instrumentation and the redundancy of critical sensors. An intensive sensor performance evaluation is ongoing.

4. The long-term stability of the segmental concrete lining seems to be confirmed from a mechanical point of view. No sign of instability was noted during these first three years of heating. The overall assessment of the concrete lining will be carried out while the experiment is being dismantled, including a complete mechanical and chemical analysis of the concrete.

5. Generally speaking, the Boom Clay behaved as expected. The observations from nearly three years of heating confirmed our knowledge of the THM behaviour of the Boom Clay gained from surface laboratory investigations and smaller-scale in-situ heating experiments:
    - In terms of temperature evolution, the comparison with the numerical predictions showed very good agreement, meaning that the heat transport mechanisms and their properties were well known even though some refinement would bring additional accuracy.
    - The clay seems to be able to sustain the thermal load without any drastic or sudden change in its hydro-mechanical properties and the structural integrity of the clay is not significantly affected by the thermal load. In fact, pore water pressure and temperature evolved smoothly. The total pressure inside the clay showed a similar increase as the pore water pressure, indicating that, during the heating phase, the effective stress in the clay around the heated gallery does not show any sharp variations and, in particular, any significant decrease that would mean a loss of contact between the clay particles, potentially leading to fracturing phenomena.
    - The fact that the numerical predictions using the continuum approach reproduced the observations relatively well suggests that no macro-cracks are generated during the heating phase and the Boom Clay maintains its structural integrity. Additionally, an extensive in-situ investigation of the intrinsic permeability showed that it did not change with the increase in temperature, confirming that the transport properties were not significantly altered during the experiment.

Further additional information and investigation will be necessary to confirm this assessment.

1.2.7 INTERIM EVALUATION SURVEY OF THE PRACLAY SEAL AND HEATER EXPERIMENTS

The PRACLAY seal and heater experiments, from the design and implementation phases through to the successful nearly three-year heating phase, have been running for a long period of time. In order to identify and formulate the most important lessons learnt and to take these into account when preparing and conducting future projects, EURIDICE embarked on an interim evaluation survey of the PRACLAY seal and heater experiments in 2016. This covered the period from the beginning of the design phase up to the end of November 2015 and consisted of two parts:

- Part 1: containing 16 multiple-choice opinion statements; and
- Part 2: including a general section asking the participants to provide additional comments, compliments, complaints and suggestions.

In addition, this survey includes recommendations obtained from in-house knowledge about the project, gathered within EURIDICE, covering aspects such as changes to project scope and project risk not included in Parts 1 and 2.

In 2017 the results of this interim evaluation survey were analysed and documented in a dedicated report, which reviews the PRACLAY seal and heater experiments and evaluates what worked well and what did not, and what lessons can be drawn, with the aim of improving quality standards, reducing project risks and delays and optimising future projects.

2. Supporting studies

2.1. Stability of the Connecting gallery

The strain inside the concrete segments and the convergence of the lining of the Connecting gallery have been monitored since the gallery was constructed in 2002. Based on these measurements, several studies have been carried out since 2013, in collaboration with ENGIE TRACTEBEL and SCK•CEN, to accurately determine the correct stress inside the concrete segments and the pressure exerted against the lining, and thus verify the stability of the Connecting gallery.

A summary of these studies was written in 2017 and will be delivered in early 2018. The main conclusion is that the state of stress inside the gallery is higher than expected (designed), but still significantly lower than the ultimate strength of the concrete. On the other hand, the studies also indicated that further analysis is still necessary to improve our understanding of the long-term evolution of the stress state inside the concrete segments by taking better account of the long-term soil-structure interaction, which is also a critical aspect for the design of the repository gallery. Finally, these studies provided an opportunity to examine our monitoring techniques with a view to improving them in the future.

2.2. Micro-seismic monitoring programme

The micro-seismic system around the PRACLAY gallery was installed in two phases between September 2006 and January 2008 and consists of 23 transmitters and 19 receivers (Figure 27 & Figure 28). The system has been operating continuously since 2006.

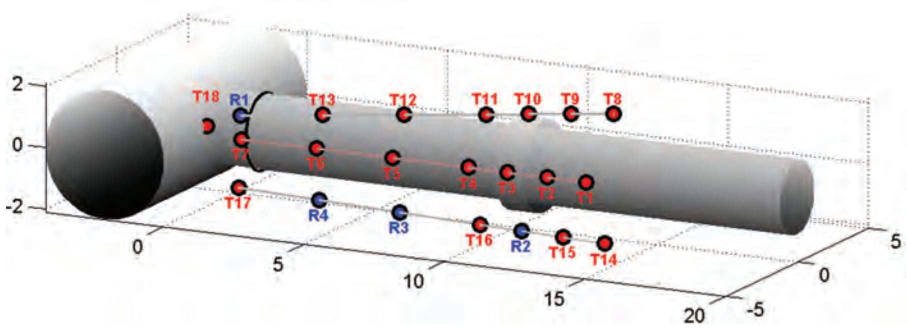


Figure 27 - [Red] transmitters (T) and [blue] receivers (R) installed in September 2006

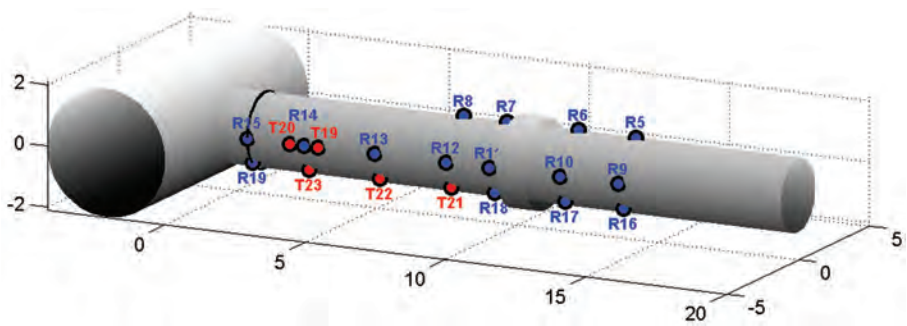


Figure 28 - [Red] transmitters (T) and [blue] receivers (R) installed in January 2008

One of the promising uses of the micro-seismic measurements is the possibility of monitoring the evolution of the seismic parameters in the clay during the PRACLAY Heater test.

An internal report has been prepared to assess the quality of the data generated by the micro-seismic set-up around PRACLAY in HADES. The report includes an overview of the data recorded so far and its quality. It also contains a preliminary analysis of the waveforms and material properties, based on measurements of compressive (P) and shear (S) wave velocities obtained on a selected number of data sets. The selection process considered the most interesting emitter-receiver pairs (based on geometry and signal transmission), as well as the different experimental phases of the PRACLAY experiment (from excavation to heating phase). This preliminary analysis shows clearly the influence of the excavation and also the effect of the bentonite swelling. However the effect of the heating phase needs more analysis. Finally, the report offers suggestions for increasing the added value of the micro-seismic set-up (from hardware refurbishment to advanced signal analysis proposals). To guarantee knowledge transfer regarding this set-up, a manual has also been written, describing the current hardware set-up and data management. There will be further discussion and a decision made in 2018 about the future deployment of this set-up.

2.3. PhD research

For the past couple of years, a specific thermo-hydro-mechanical-chemical (THMC) characterisation programme on the Boom Clay has been run in parallel with the PRACLAY experiment, in collaboration with different universities and laboratories through several PhD research projects. EIG EURIDICE is involved in the definition and supervision of these projects.

Late 2015 marked the end of one phase of this THMC characterisation programme: most of the contractual PhD research projects for the period 2010-2015 terminated at the end of 2015, except the cooperation project with the Institute of Rock and Soil Mechanics (IRSM) of the Chinese Academy of Science (CAS) on the long-term THM behaviour of the Boom Clay. This project needs to be extended to be able to finish the initially planned long-term creep tests under well-defined THM boundary conditions. The PhD project conducted in collaboration with the International Centre for Numerical Models in Engineering (CIMNE), Spain, on the laboratory investigation of gas transport in the Boom Clay was also extended for one year to enhance the laboratory evidence and to improve the interpretation through numerical modelling. The thesis was defended in May 2017.

Since 2016 EURIDICE, together with SCK•CEN's "Waste & Disposal" (W&D) Expert Group, has annually introduced one joint PhD research project within the PhD programme for Young Potentials at SCK•CEN's Academy. In 2016 one project, entitled *A Multiscale Approach to Model Early Age Thermo-Hydro-Mechanical Behaviour of non-reinforced Concrete*, was awarded to Saeid BABAEI, who started working on it in January 2017. This is financed by SCK•CEN's Academy and is being pursued in collaboration with Antwerp University. Another project, entitled *Investigation of the long-term behaviour of Boom Clay*, was introduced and approved in 2017. This project will be co-funded by ONDRAF/NIRAS and SCK•CEN's Academy and will be a joint collaboration with Laboratoire Navier/CERMES, l'École des Ponts ParisTech.

CIMNE (Universitat Politècnica de Catalunya, Barcelona (UPC), Spain)
Financed directly by ONDRAF/NIRAS, PhD research on the *Laboratory investigation of gas transport processes in Boom Clay* was initiated at the end of 2012 by Laura Gonzalez-Blanco. Together with ONDRAF/NIRAS, EIG EURIDICE was involved in supervising and following up the project.

This research aimed to study the gas transport mechanisms and breakthrough processes in the Boom Clay through an exhaustive laboratory experimental programme. One of the important issues in the long-term performance of a geological repository concerns the generation and migration of gases that can be produced as a result of the anaerobic corrosion of metal canisters, radiolysis, microbial degradation of organic waste, etc.

The thesis was defended in May 2017. The collaboration associated with this project has led to several joint publications (see Scientific output).

IRSM (Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, China)
The project *Research on long-term coupled thermo-hydro-mechanical (THM) behaviour of the Boom Clay* aims to investigate the effect of temperature on the creep and self-sealing capacity of the Boom Clay and to gain knowledge and information for simulating the PRACLAY Heater test. This project started in late 2011 and was concluded at the end of 2015.

A complete test programme has been established within the context of this collaboration agreement. This programme covers a set of short-term tests (odometer tests, triaxial tests at different temperatures, permeability tests, etc.) and long-term (creep) tests (odometer and triaxial). The long-term creep tests were aimed at investigating the deviatoric stress threshold for creep and temperature effects on the creep behaviour; particular attention was also devoted to creep behaviour during the heating/cooling cycle, which mimics the thermal path around an HLW repository.

Due to the low permeability of the Boom Clay, the laboratory tests, especially the creep tests on the Boom Clay, are extremely time-consuming. It was decided together with ONDRAF/NIRAS to continue the experimental study of the Boom Clay with IRSM. This study mainly aims to finish the planned experimental programme and especially the creep tests to fill some of the knowledge gaps identified regarding creep behaviour and provide more data to calibrate the parameters of the EVP-Damage model of the Boom Clay developed at IRSM based on laboratory tests.

In 2016 a new THM-coupled triaxial testing machine was specially designed, updated and calibrated for the THM-coupled triaxial compression and creep tests on the Boom Clay.

In 2017 six creep tests at different temperatures and under low deviatoric stress (< 1 MPa) were performed. The main objectives were to determine the stress threshold (if it exists) of the creep under different temperatures with heating/cooling cycle.

New test results were compared with those under higher deviatoric stress (> 1 MPa). In general, the following observations were obtained:

- Most of the test results indicated that the creep strain at lower deviatoric stress (< 1 MPa) is insignificant compared with that under higher deviatoric stress (> 1.0 MPa). This observation remains true at different temperatures.
- Under higher deviatoric stress (> 1 MPa), the creep strain is highly dependent on the temperature and confine pressure (as shown in Figure 29). The higher the temperature, the higher the steady creep strain rate. The higher the confine pressure, the lower the steady creep strain rate.
- During the cooling phase, the creep strain is negligible; this remains true, regardless of the confine stress.

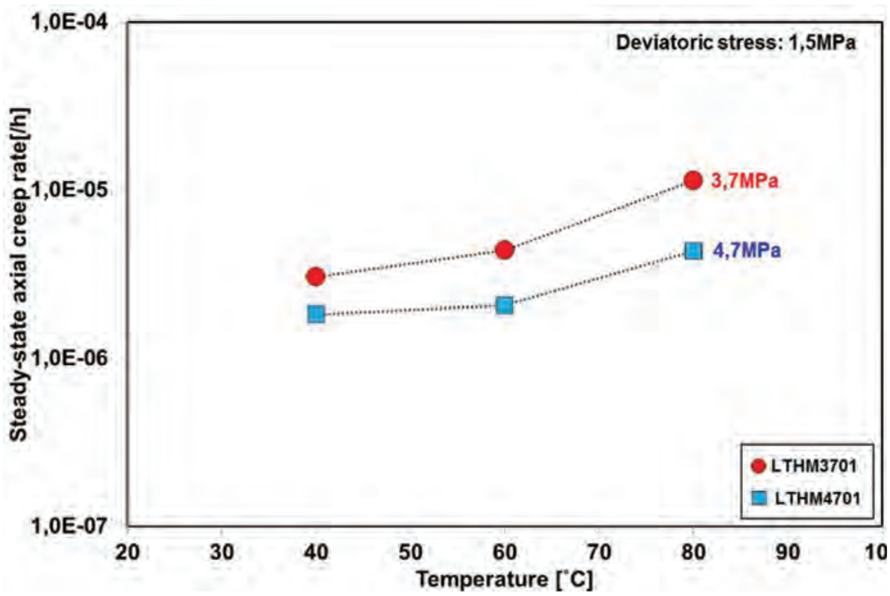


Figure 29 - Temperature influence on the steady-state creep rate

However, some tests also provided some scatter results. More tests are required to check these observations, especially the effect of the deviatoric stress on the creep rate.

Joint PhD project between EURIDICE and SCK•CEN's W&D

As part of a joint research initiative between EURIDICE and SCK•CEN's W&D Expert Group, work began on a PhD research topic in late 2016 in collaboration with the University of Antwerp, entitled *A Multiscale Approach to Model Early Age Thermo-Hydro-Mechanical Behaviour of non-reinforced Concrete*. This research has direct relevance to concrete engineered barriers, which are an integral part of nuclear waste disposal concepts developed in Belgium.

The research focus is on drying shrinkage and creep phenomena at an early age. The initial work mainly concentrated on establishing the state of the art of theoretical developments in drying shrinkage problems. One of the key inputs to study drying shrinkage is the hydraulic properties of cement paste, such as moisture retention characteristics, unsaturated hydraulic conductivity and diffusivity. The objective is to obtain these properties based on the fundamental characteristics of cement paste at the pore scale. To this end, a pore network model was implemented, in which fundamental thermodynamic equations were encoded and validated against experimental data. Various poroelasticity approaches were then considered to evaluate drying shrinkage strains and compared with experimental data.

An existing fully coupled thermo-hydro-mechanical model for soils was adapted for the cement paste material, including an extension to accommodate damage mechanics capability. This makes it possible to predict damage propagation due not only to drying shrinkage but also to thermally driven processes. The coupled model is fully tailored to handle mesoscale problems, such as the inclusion of aggregates and interfacial transition zones.

So far some of the results of the above work have been disseminated in the form of posters during the PhD day organised by SCK•CEN and at a recent training workshop in Poland. Currently, two papers are being drafted for two international conferences: (i) the 4th International Conference on Service Life Design for Infrastructures in Delft (72^{nd} RILEMWEEK), and (ii) the Sixth International Symposium on Life-Cycle Civil Engineering in Ghent.

2.4. Core Management & GSIS

EIG EURIDICE coordinates the management of ONDRAF/NIRAS drill cores. This includes packaging cores to ensure good preservation during long-term storage, making an inventory of the cores of both HADES drillings and regional drillings, and managing and processing core requests for R&D from ONDRAF/NIRAS, SCK•CEN or other research institutes as part of the Belgian radioactive waste disposal programme.

EIG EURIDICE is also responsible for further development and support of the GSIS database (GeoScientific Information System). This is an integrated database that centralises all data concerning drilling, drilling cores, piezometers, samples, analyses, etc. in the context of the Belgian radioactive waste disposal programme, and ensures the traceability of validated geoscientific data.

In 2017 the procedure for core requests was reviewed, simplified and further improved. The main activities in 2017 related to the implementation of core management in GSIS and further adaptation of the core management procedure, resulting in simplification of the process. The required changes in the database structure (already carried out in 2016), comprising the visibility of available/non-available cores, core storage details and a "tracking" metadata table, were made in order to include data required by the core management procedure. Based on the data from the ON-Mol-1 borehole, a model core request was processed to identify potential gaps in the database structure and/or interface. The user interface now displays the following information at a glance in the summary list of core selections: core identification (number and section), depth in BDT (depending on chosen reference point – BDT, BGL), depth in TAW, availability yes/no, core track information (used for research) and comments. Another new feature included in GSIS is the object log, which gives the user an opportunity to add details on object handling as an attachment to any object, thus making the handling history (for example in the case of cores) traceable. The core management process can benefit from the existing GSIS feature of creating public selections, which can be used for preparation and approval of the core pre-selections in GSIS.

The adaptation to the database structure and interface can only be fully used if all existing information is included in the database. We therefore continued working on gradually completing data input. The most important activity here was the update of the availability of the ON-Mol-1 cores. The input of the ON-Mol-2A and ON-Mol-2D boreholes is planned for early 2018. Data input of the HADES boreholes, piezometers and cores is also gradually being completed.

The representation of 3D objects (HADES URL) is indispensable when introducing 3D geometries (to check their correctness) and for effective visualisation of the 3D coherence of objects and data. Similar to the map view, the 3D view makes it possible to see all objects in a selection within a 3D space. This feature was developed in 2017 and implementation in the production server is planned for June 2018.

Finally, efforts were made to enhance the general user experience. The entire design of the interface was updated, resulting in an adaptive web design that optimises user experience for different screen sizes. This feature will be implemented in the production server in June 2018.

3. Instrumentation & Monitoring

Since the installation of the first experimental set-ups in HADES in the 1980s, a great deal of monitoring experience has been gained in the use and long-term performance of sensors in repository-like conditions. This is one of the areas of expertise of EIG EURIDICE. The whole monitoring programme has been formalised since 2016 through the Monitoring Task Package agreement with ONDRAF/NIRAS. In 2017 this programme consisted of three studies: (1) the finalisation of the review of instrumentation performance of the CAS set-up, (2) the development and testing of a methodology to assess non-accessible sensors, and (3) the development of a data management methodology. Finally, a new task has been initiated, namely an interim assessment of the PRACLAY instrumentation set-up.

The first study deals with the review of the instrumentation installed as part of the CLIPEX project. The aim of this project, which ran from 1997 to 2002, was to assess and characterise the hydro-mechanical disturbance of the Boom Clay and, more specifically, the EDZ during the excavation of the Connecting gallery (early 2002). The monitoring system consisted of instrumented boreholes installed from the Test Drift front and from the second shaft prior to the excavation of the Connecting gallery (cf. Figure 1). In addition, the instrumented lining segments were part of the CLIPEX monitoring programme. The monitoring data included pore water pressure, total pressure, displacement and deformation. Initiated in 2015, the actual assessment methodology – being applied here for the first case – consisted mainly of a systematic description in an overview table of the actual performance of each individual sensor. Performance was assessed by considering various criteria, ranging from installation issues and sensor reliability with time to actual accuracy and signal quality. After several discussions to clarify the scope and methodology of the study, a final draft report on the performance assessment of the instrumentation in the CLIPEX set-up was delivered in 2017 to ONDRAF/NIRAS, where it is currently under review. The draft comprises performance tables, with an assessment of each individual sensor, as well as a more general review, including the context of the sensor assessment, the current state of the art of the monitoring technologies considered (e.g. whether the sensors used in CLIPEX are still technologically relevant), and the prospects of using such sensors in future large-scale demonstration programmes (or, eventually, in a repository).

The second study deals with diagnostic techniques that can be applied to non-accessible sensors. Once installed, many sensors used in the (geotechnical) context of a repository (such as in URLs) are no longer accessible for maintenance, replacement or calibration. This makes it more difficult to interpret the sensor signal in the event of any deviating or unexpected measurement data. To assess the measurement results from these sensors, a specific study is devoted to exploring the diagnostic methods that could be used to check the reliability of such sensors, and the related measurement results. In 2017 efforts focused on a specific test method to verify the correct functioning of thermocouples, one of the most common sensors in our experimental set-ups, and probably also an essential sensor type in future programmes. The work done last year involved developing test methods based on the symmetric nature of thermocouples (thermal conditioning of the accessible, cold junction), and simulating sensor failures by accelerated corrosion of a thermocouple.

The third study tackles the data management issue. The PRACLAY experiment, as well as other experimental set-ups, has made it clear that data management in a repository context requires a specific approach, which should take into account aspects ranging from technical issues (e.g. non-accessible sensors and long-term reliability) and specific organisational matters (long-term follow-up, distributed and varying monitoring configurations, etc.) to strategic considerations such as the use of the data by different stakeholders (scientists, decision-makers, local citizen stakeholders, etc.). This study was initially aimed at developing a methodology for the management of repository data, based on the experience acquired to date. It covers a range of topics, from planning a monitoring system to follow-up and data validation. At the start of the study, it became clear that the initial focus on repository monitoring should be replaced by a more concrete objective relating to data management for demonstration tests, which could be put to use for the generation of validated data sets, for example. The study is now considering current practices in similar fields (e.g. geotechnical monitoring), and also reflecting on the data management experiences of PRACLAY. Based on the first drafts produced in 2016, there were internal discussions in 2017. At the end of 2017, it was agreed with ONDRAF/NIRAS that the current study would be finalised. Future work on these issues will be discussed with ONDRAF/NIRAS in 2018.

4. Participation in international research projects

4.1. European Commission (EC) projects

Modern2020

Within the framework of the Horizon 2020 Euratom Work Programme NFRP6-2014 “Supporting the implementation of the first-of-the-kind geological repositories”, a new project to monitor geological radioactive waste repositories, called “Modern2020”, was approved by the EC early in 2015. The project started on 1 June 2015 and will run for 48 months. The project consortium is made up of 28 partners from 12 countries.

In the project summary of the Modern2020 project, the general objective is stated as follows:

“The Modern2020 project aims at providing the means for developing and implementing an effective and efficient repository operational monitoring programme, taking into account the requirements of specific national programmes.”

The project consists of four technical work packages (WPs), and EURIDICE is participating in two of these: WP3 (Monitoring Technology) as coordinator/advisor and WP4 (Demonstration and Practical Implementation) as Work Package Leader. The other two WPs are Strategy (WP2) and Societal Concerns and Stakeholder Involvement (WP5).

In WP3, EIG EURIDICE is contributing to four tasks, where it mainly has an advisory and coordinating role in the development of new fibre-optic sensors, the integration of these sensors with wireless transmission, and the testing and validation of the devices in repository-like conditions. In 2017 EURIDICE contributed to the integration of the components of the fibre-optic monitoring system (based on Fibre Bragg Grating - FBG) and first demonstration in close collaboration with the University of Mons, for the development of specific FBG sensors, and with Com&Sens, a Ghent University spin-off and subcontractor of EIG EURIDICE in this project, which has developed a miniature interrogator (optical spectrum analyser) for these FBG sensors. Another achievement in 2017 was the design and implementation of an irradiation programme for these sensors at SCK•CEN – the irradiation programme will continue until early 2018.

WP4, in which EURIDICE is the Work Package Leader, brings together demonstrator set-ups that are being developed and are or will be operated in foreign URLs: Finland (Olkiluoto), France (Bure and Tournemire) and Switzerland (Mont Terri). In addition, this WP also revisits some existing cases, which will be re-assessed with the focus on monitoring experience that is relevant for repository operation, such as the use of monitoring data for decision-making, or the involvement of local stakeholders in the field set-up. As this WP partly builds on the results of WP2 and WP3, the actual work did not start at the beginning of the project. To assess the current situation, EURIDICE organised a two-day workshop at Mont Terri (CH), during which the current status of the four demonstrators, ranging from desk studies to functional set-ups, was presented. In addition, the interaction with the other WPs (WP2 on monitoring strategy, WP3 on technology, and WP5 on citizen and other stakeholder involvement) was further explored. There was also an initial exchange of thoughts on the fifth task within WP4, where existing cases will be “revisited” to look in particular for repository monitoring-related experience that has not necessarily been documented.

During a first meeting organised by the University of Antwerp, EURIDICE also expressed an interest in contributing to the Monitoring School (planned in spring 2019 at Äspö, Sweden) and to the compilation of the Monitoring Handbook, which is also intended to be used by the larger stakeholder community.

4.2. Other international collaborations

In 2017, together with SCK•CEN's W&D Expert Group, EURIDICE responded to a call for expression of interest from the EURATOM call to prepare two RD&D work packages to be launched in 2019 within the forthcoming European Joint Programme on Radioactive Waste Management and Disposal:

- Influence of temperature on clay-based material behaviour
- Mechanistic understanding of gas transport in clay materials

Xiangling Li was guest editor of a special issue of the *Journal of Rock Mechanics and Geotechnical Engineering* on the topic of "geological disposal of nuclear waste" (Volume 9, Issue 3, Pages 383-574, June 2017). Sixteen articles were accepted for this special issue, including contributions from EURIDICE, ANDRA, NAGRA, FANC and universities/institutes.

Two Chinese visitors, Dr Hongdan Yu and Dr Haifeng Lu, sponsored by the Chinese Academy of Science (CAS), undertook a one-year scientific visit to EURIDICE, starting in May 2016. During their stay, they worked on the following two topics:

- "Knowledge consolidation on the laboratory test results related to the thermao-hydro-mechanical behaviour of Boom Clay" (Dr Hongdan Yu)
- "Knowledge consolidation on the in situ test results related to the hydro-mechanical behaviour of Boom Clay" (Dr Haifeng Lu)

Romain Brebonne, a Master's student in bio-engineering (University of Liège), completed a two-month internship at EURIDICE as part of the SCK•CEN Academy programme. The main focus of his work was to produce a synthesis report on Boom Clay properties in frozen conditions. Our knowledge of this subject was acquired more than 30 years ago so the aim was to update it. In addition, he provided support for the mechanical analysis of the Connecting gallery by creating an Excel macro to calculate the stress from the measured strain in the concrete segments of the gallery. This work was very important to enable us to continue properly monitoring the gallery's mechanical state of stress.

Arnaud Dizier was invited as an external examiner for the defence of a Master's thesis in civil engineering by Pacifique Narame from the University of Liège. The subject of this work was: "Étude expérimentale du comportement mécanique et de la perméabilité de mélanges bentonite – sable" (Experimental study of the mechanical behaviour and permeability of a bentonite-sand mixture).

JRC-Geel
Since 1999 EIG EURIDICE has delivered services for JRC-Geel's long-standing operation of an ultra-low-level radioactivity laboratory in support of European Commission policies in such fields as international standardisation, radioactive waste management and radioprotection. Some key projects in 2017 included: characterisation of reference materials for food safety and nuclear decommissioning, radiotracer studies of water from the Pacific Ocean to determine the transport of iron from hydrothermal vents, which contributes significantly to the ocean's ability to bind CO_2, and support to international research groups performing studies on rare nuclear decays and fusion research. The latter projects were carried out within JRC-Geel's external access programme. One particular highlight was the paper published in *Nature* on the GERDA experiment to detect neutrinoless double-beta decay. This experiment is underway in Italy, but all 35 detectors used in the experiment were tested and characterised in HADES. It was the second most commented paper from JRC-Geel in 2017.

For the purpose of this research, part of the HADES URL has been leased to JRC-Geel. The contract is a Service Agreement that can be extended on a yearly basis.

5. Specific support for ONDRAF/NIRAS's study on the technical feasibility of geological disposal

EIG EURIDICE supports ONDRAF/NIRAS in its RD&D programme on the technical feasibility of a geological disposal facility. This programme aims to demonstrate the feasibility of the construction, operation and closure of the proposed concept for geological disposal of nuclear waste.

Within this context, the studies carried out by EURIDICE, or in which it participates, cover the following topics:

- Design and fabrication of the disposal waste packages, in particular the supercontainer
- Excavation and construction techniques for the shafts and galleries of an underground repository
- General support for the geological disposal facility design
- Operation and closure of the underground facility

Thermal analysis of a geological disposal facility for high-level radioactive waste in clay formations
ONDRAF/NIRAS considers geological disposal in poorly indurated clays to be an option for the management of category B (low-level and intermediate-level long-lived waste – LILW-LL) and C waste (high-level waste – HLW and spent fuel). This option involves using either the Boom Clay or the Ypresian clays as a potential host rock. These clays are present in continuous strata in the north of Belgium down to a depth of 600 m. One proposed option for the management of category B and C waste is thus geological disposal in poorly indurated clays at a depth of between 200 and 600 m. For the period 2015-2020, ONDRAF/NIRAS is preparing the first Safety and Feasibility Case (SFC-1 V1) for the geological disposal of category B and category C radioactive waste.

Within this context and at the request of ONDRAF/NIRAS, EURIDICE has developed a numerical model to simulate the thermal response of the geological disposal facility when heat-emitting C waste (future vitrified waste (CSD-V) or spent nuclear fuel assemblies (UOX - 8ft, UOX - 12ft, UOX - 14ft and MOX)) are placed in the disposal galleries. The numerical model was developed using the finite element software COMSOL multiphysics© and is able to calculate the temperature evolution in both the engineered barrier system (EBS) and the natural barrier system (NBS) in the Boom Clay and the Ypresian clays, respectively.
The ultimate objectives of the research are:

- To identify the most significant parameters for the temperature evolution in the EBS and in the NBS;
- To evaluate the temperature field inside the geological disposal facility (i.e. inside the EBS and the NBS) for the three reference depths (200 m, 400 m and 600 m).

The EBS for the C waste consists of the following components:

- The supercontainer (carbon steel overpack, cementitious filler, concrete buffer and stainless steel envelope), as shown in Figure 30;
- The cementitious backfill filling the gap between the supercontainer and the concrete support of the disposal galleries;
- The concrete segmental lining of the disposal galleries.

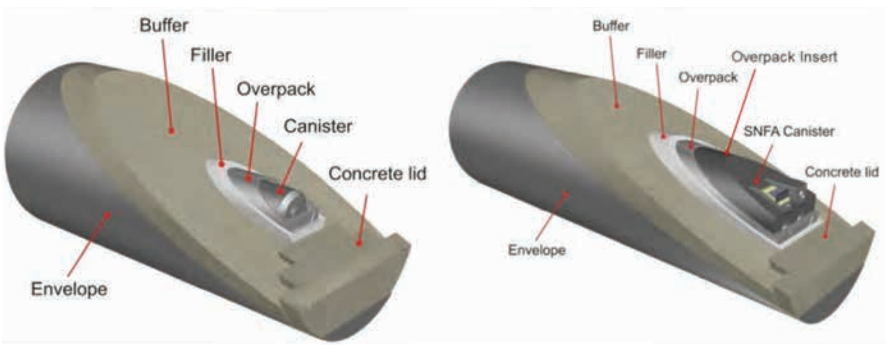


Figure 30 - Supercontainer layout

The research took into account poorly indurated clays of both the Boom Clay and the Ypresian clays, and evaluated the impact of the depth of the potential repository. Three depths were taken into account i.e. 200 m, 400 m and 600 m. The potential geological disposal facility in the Boom Clay can be at 200 m or at 400 m. In the Ypresian clays, all three potential depths are possible in Belgium. Five types of supercontainer were also considered: SC-1 (CSD-V or vitrified waste), SC-2 (UOX - 8 ft), SC-3 (UOX - 12 ft), SC-4 (UOX - 14 ft) and SC-5 (MOX).

For the near-field analysis, in and around the EBS, a 2D axisymmetric model was developed. For the far-field analysis, at the transition between the clay and the aquifer, a 2D plane model representing a slice or a section across a geological disposal facility is used. Figure 31 shows the finite-element model of the EBS simulation for the near-field calculation and the resulting temperature profiles in the EBS for SC-4 (UOX - 14ft). The first results for all types of supercontainer will be available in 2018.

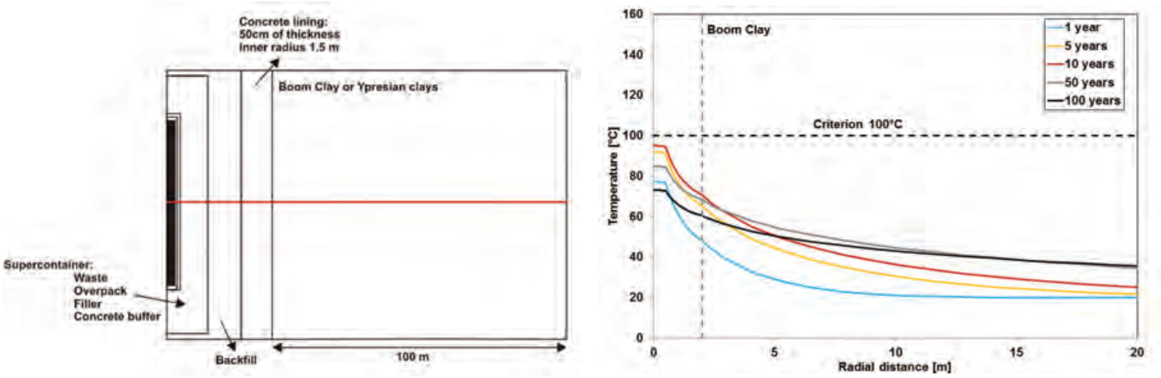


Figure 31 - Finite-element model (idealised geometry, in red the line where the temperature profiles were calculated) for the EBS simulation and temperature field in the EBS (supercontainer with UOX - 14ft)

6. Support for Safety and Feasibility Case 1 of ONDRAF/NIRAS

EIG EURIDICE provides scientific and technical expertise for the development of ONDRAF/NIRAS's first Safety and Feasibility Case (SFC-1), which is scheduled for 2020. In particular, it supports ONDRAF/NIRAS by writing state-of-the-art reports on the properties of clays and their mechanical, hydraulic and thermal behaviour, based on studies carried out by EURIDICE and its partners. EURIDICE regularly provides topical documents on specific aspects of the geo-mechanical behaviour of the Boom Clay as observed around the HADES URL. EURIDICE is also in charge of the daily management, follow-up, scientific operation and reporting of the long-term, large-scale PRACLAY Heater test. Scientific publications and a report presenting the results from the first few years of this experiment (2014-2018) and their interpretation will constitute a significant input to the SFC-1.

7. Support for the general RD&D programme of ONDRAF/NIRAS on geological disposal in clay host rocks

As manager and operator of the HADES URL, EIG EURIDICE also supports ONDRAF/NIRAS and its research partners by providing samples, data and expertise for studies carried out in collaboration with third parties in various scientific fields of importance for geological disposal in clay. Typical research topics include the characterisation of the components of the Boom Clay, its pore structure, pore water chemistry, solute, gas and heat transfer mechanisms, microbial activity within and around underground structures, etc.

Activities: PART II

The surface disposal programme for category A waste - cAt Project

Introduction

On 23 June 2006 the Belgian federal government decided that the long-term management of category A waste should take the form of a surface disposal facility within the municipality of Dessel, situated in the northern, Flemish part of Belgium in the Province of Antwerp. The government commissioned ONDRAF/NIRAS to carry out this integrated programme – i.e. the cAt project. To fulfil its appointed task, ONDRAF/NIRAS works in close collaboration with the STORA and MONA partnerships it has with the municipalities of Dessel and Mol, respectively.

An important step in the successful completion of this project has been the licence application that ONDRAF/NIRAS submitted on 31 January 2013 to the Belgian nuclear regulator, the Federal Agency for Nuclear Control (FANC), for the surface disposal facility. In 2017 FANC confirmed that its questions had all been answered and asked for the licence application documents to be updated with the changes resulting from these answers.

EIG EURIDICE supports the cAt project in the following areas:

- Calculations of the long-term radiological impact of the planned disposal facility;
- Calculations and validation tests of the hydrogeological models used in the licence application for the planned disposal facility;
- Preparation and instrumentation of the planned test cover;
- Instrumentation of the demonstration test for construction of concrete modules.

1. Radiological long-term safety assessments and quality assurance of models and codes

Radiological long-term safety assessments, prepared and documented during the period 2010-2012, are a key part of the safety arguments presented in the licence application.

After examining the licence application, FANC asked several questions on the phenomenological basis of the radiological long-term safety assessments and on the safety assessments themselves. In 2015 this resulted in a revision of the expected evolution of the disposal facility after its closure. Subsequently, the changed expected evolution needed to be reflected in changes to the assessment cases, which had to be re-calculated.

In 2017 the revised altered evolution scenarios were defined, re-calculated and reported. These new calculations formed the basis for answering FANC's final questions about the long-term safety assessments.

2. Hydrogeological models

FANC's analysis of the licence application also led to questions on additional validation of the hydrogeological models. In order to comply with FANC's demand to validate the local groundwater model, field tests were performed to determine the groundwater flux in the shallow part of the aquifer.

Point dilution tests in some piezometers, situated south-east of the eastern tumulus, proved to be unreliable, probably due to a corroborated poor connection between the host formation and the filter. The drilling of new "dilution test wells" was planned in four locations on the disposal site. These piezometers were installed using a new drilling technique, whereby backfilling of the annulus can be avoided. The first dilution tests in these new piezometers were carried out in spring. The dilution test campaign will continue in all piezometers (9) on a seasonal basis for the next two years.

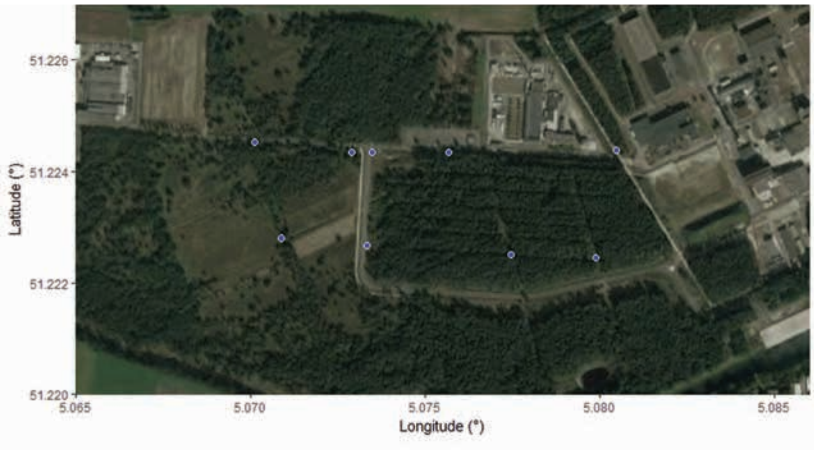


Figure 32 - Location of the nine piezometers used for point dilution tests, part of the additional experimental programme for validation of the hydrogeological models

3. Test cover

As construction of the test cover has been postponed, work focused on prototype testing in 2017. Two new prototypes were tested: an infiltrometer to measure in situ the hydraulic conductivity (Ks) of the compacted clay layers installed, and a sediment trap to quantify the amount of eroded sediment present in the run-off water on top of the cover. With respect to Ks measurements, two infiltrometers were built: a larger one for Ks determination tests (lasting several days (or even weeks)) to be performed on compacted clay layers from an on-site lab, and (2) a smaller device for testing during construction whether each installed clay layer has a sufficiently low permeability. A test with this smaller device should last only 1 or 2 hours. These two infiltrometers were tested on the clay tumulus of the test cover and were found to work correctly.

Testing of the sediment trap that was developed was not conclusive. In fact, the filter used to catch the sediment while letting the water pass through appeared to clog fairly quickly. And once clogged, the filter then started to hold up water as well. The choice of filter mesh is of paramount importance: a fine mesh will capture most of the sediment (including the finer fractions) but will be prone to rapid clogging, thereby leading to a loss of sediment by overflow. However, a coarser filter mesh will miss the finer fractions, which make up an important part of the run-off sediments during severe rainfall. The design of the sediment trap will therefore have to be adapted.

In addition, the test of the designed prototype for subsurface CO2 monitoring that was initiated in 2014 was continued in 2017 (Figure 34). This prototype still works fine.

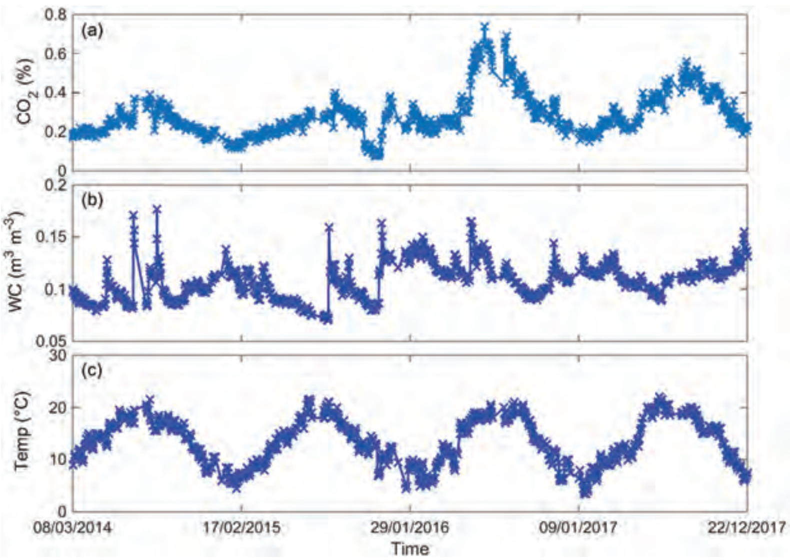


Figure 33 - Time evolution of (a) the measured CO2 concentration, (b) water content (WC) and (c) temperature (temp) during the soil CO2 sampling field experiment

4. Demonstration test

In order to assess the technical feasibility of the module construction techniques and the industrial feasibility of the concrete that has been optimised for long-term safety and has been tested on a laboratory scale, a demonstration module construction test for the cAt project has been underway since 2011 (Figure 34).

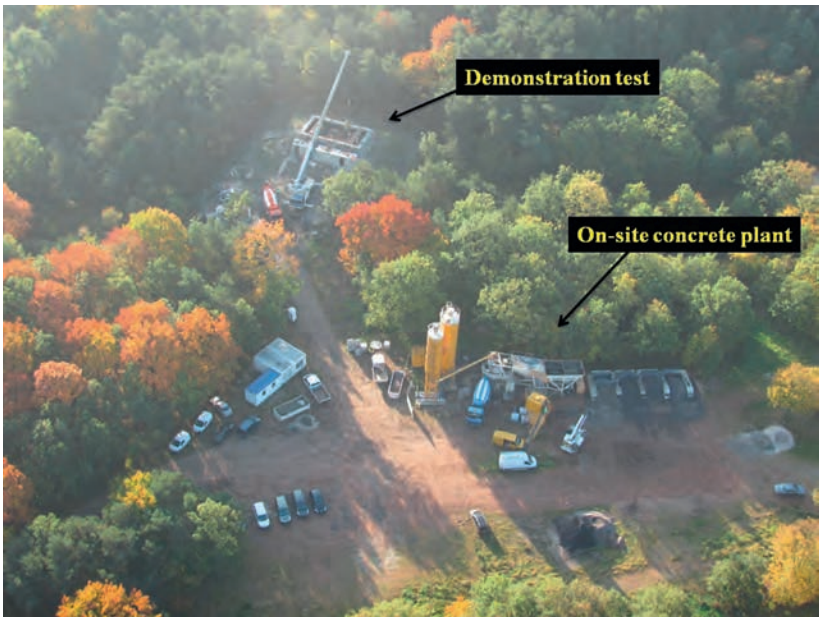


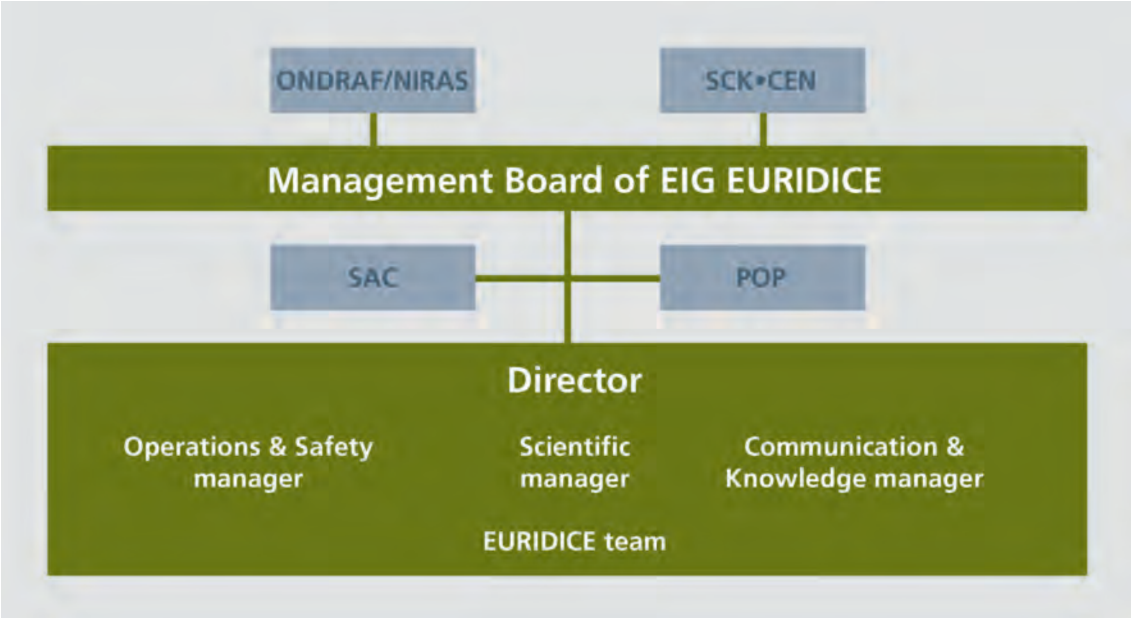
Figure 34 - Overview of the demonstration test

EIG EURIDICE, together with ONDRAF/NIRAS and Tractebel Engineering, has devised an instrumentation plan for assessing the temperature and stress conditions within the concrete used in the demonstration test.

There was no on-site construction work in 2017. Some data collection and analysis continued, however.

General Management of EIG EURIDICE

1. Organisation



EIG EURIDICE is governed by a four-person **Management Board**. ONDRAF/NIRAS and SCK•CEN each appoint two board members for a period of three years. The Chairman of the Board is appointed by ONDRAF/NIRAS. The Secretary of the Board and the Director of EURIDICE attend meetings in an advisory capacity.

The board members as at the end of 2017 are as follows (June 2016 - June 2019):

- Marc Demarche, Chairman, Director-General of ONDRAF/NIRAS
- Philippe Lalieux, Director long-term management ONDRAF/NIRAS
- Eric van Walle, Director-General of SCK•CEN
- Hildegarde Vandenhove, Director of the Environment, Health and Safety Institute of SCK•CEN

Responsibility for the day-to-day management of EURIDICE lies with the Director and the Scientific Manager, who are appointed by ONDRAF/NIRAS and SCK•CEN, respectively. They are supported in their task by the Operations & Safety Manager and the Communication & Knowledge Manager.

EIG EURIDICE's main activities in relation to geological disposal RD&D and the management and operation of all EURIDICE facilities for the period 2015-2020 are defined in a contractual agreement with ONDRAF/NIRAS (ESV EURIDICE CO2015_RA_EUR_15-116). This agreement also specifies the total budget available.

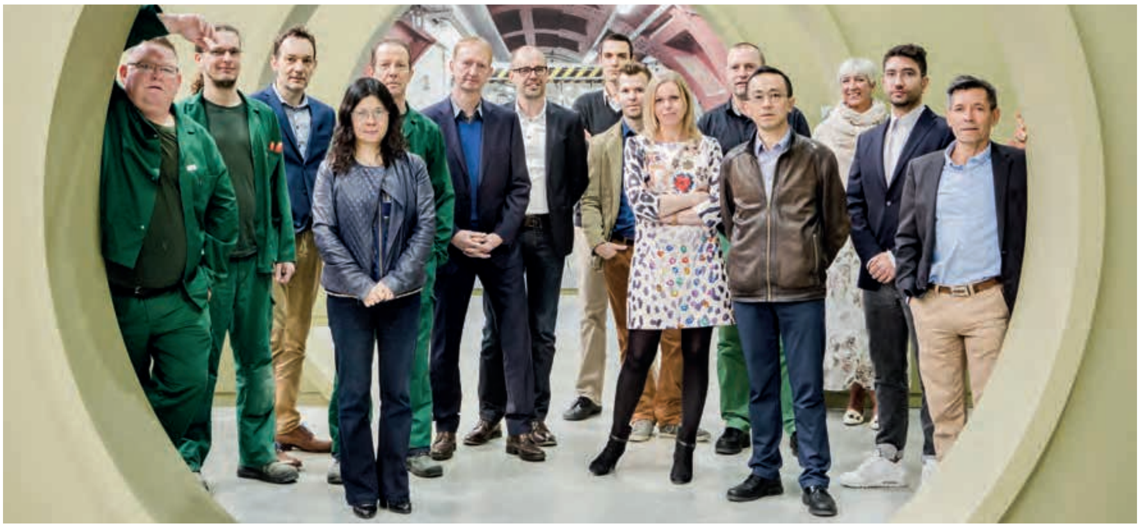
In 2017, in interaction with its constituent members SCK•CEN and ONDRAF/NIRAS, EIG EURIDICE continued the strategic review of its statutory tasks, organisation and operation, with a view to improving its future performance in support of its two members. During 2017, proposals were formulated by the ad hoc EURIDICE Task Group to the EURIDICE Board:

- Continuation as an Economic Interest Grouping and extension of the EIG's lifetime;
- Continuity of the statutory tasks, with increased emphasis on project and knowledge management;
- Creation of an RD&D platform to coordinate RD&D work with the members and in the HADES URL (replacing the existing POP committee), and to define and organise the external review and advisory function (replacing the existing SAC committee – see also point 3 below);
- To organise staff support by the members through a collaboration agreement;
- To clarify and enhance the legal guarantees for the two members regarding the future use of the HADES URL.

The EURIDICE Board has approved in principle the Task Group's proposals, so that the Task Group can propose the necessary modifications to the EIG's Statutory Rules with a view to having these approved by the members in the first half of 2018.

2. EIG EURIDICE team

Under its Statutory Rules, EIG EURIDICE has no employees of its own. Personnel working for EIG EURIDICE are under contract to either SCK•CEN or ONDRAF/NIRAS and operate as the EIG EURIDICE team, based at the EIG EURIDICE site.



Director
Peter De Preter

Scientific team
Xiangling Li - scientific manager
Lou Areias - scientific collaborator
Arnaud Dizier - scientific collaborator
Guangjing Chen - scientific collaborator
Ioannis Troullinos - scientific collaborator
Jan Verstricht - scientific collaborator

Technical team
Jef Leysen - operations & safety manager
Luc Mariën - project engineer
Hendrik Huysmans - operation technician
Christian Lefèvre - operation technician
Johan Peters - operation technician
Bert Vreys - operation technician

Office manager
Caroline Poortmans

Organisation of visits
Els Van Musscher

Communication & Knowledge manager
Jan Rypens

Scientific Visitors in 2017
Hongdan Yu - associate professor at IRSM•CAS, China
Haifeng Lu - associate professor at Wuhan University, China
Romain Brebonne - a Master's student in bio-engineering at Liège University

3. Scientific Advisory Committee (SAC)

The two constituent members of EIG EURIDICE each appoint three external experts for a period of four years.

The members appointed by SCK•CEN for the period June 2013 – June 2017 were:
- Prof. Robert Charlier, Professor of Geotechnical Engineering and Soil and Rock Mechanics at Liège University (Belgium)
- Prof. Geert De Schutter, Professor of Concrete Technology at Ghent University and Technical Director of the Magnel Laboratory for Concrete Research (Belgium)
- Prof. Tilmann Rothfuchs, Retired Head of GRS (Gesellschaft für Anlagen und Reaktorsicherheit) -division of Repository Safety Research (Germany)

The members appointed by ONDRAF/NIRAS for the same period were:
- Dr Gilles Armand, Head of the Fluid and Solid Mechanics Department at the French National Agency for Radioactive Waste Management - ANDRA (France)
- Prof. Jean-Marc Baele, Professor of Geology and Applied Geology, University of Mons (Belgium)
- Prof. Philippe Claeys, Head of the interdisciplinary research unit Earth System Sciences, Vrije Universiteit Brussel (Belgium)

EURIDICE organised one SAC meeting in 2017, on 11 May 2017, during which the status of the PRACLAY heater experiment after more than two years of heating was discussed. EURIDICE also informed the SAC members about its intention to reorganise the external review and advisory function in the future, and expressed its appreciation to all SAC members for their valuable scientific contributions to EURIDICE's RD&D work.

4. Management, operation & safety of installations

GENERAL

The Statutory Rules define the responsibilities and tasks of EIG EURIDICE concerning the management and operation of the installations on the land for which EIG EURIDICE holds a building lease. In 2017 these tasks were performed in accordance with applicable regulations, ensuring safe operations.

Under the agreement between EURIDICE, SCK•CEN and ONDRAF/NIRAS, which defines the safety structure of EIG EURIDICE, monthly meetings were organised between representatives from the three parties. These meetings mainly focused on fire safety, the nuclear licence, the training programme and the electrical installations.

Besides all routine activities relating to maintenance, checks and inspections of machinery and installations, a general and systematic safety evaluation of all EURIDICE's activities is ongoing. In this systematic safety evaluation, the main priorities are once again fire safety, the training programme and the electrical installations.

The operations team gave technical support to RD&D activities in different projects and also to communication activities:
- Connection of monitoring devices to the data-logging system in HADES;
- Technical support to the PRACLAY seal and heater experiment;
- Operation of the hoisting system and technical assistance during visits;
- Core drillings for Boom Clay sampling.

UNDERGROUND INSTALLATIONS AND ASSOCIATED HOISTING SYSTEMS

The operations team and/or AIB Vinçotte carried out the necessary checks and inspections on the shafts, cables and hoisting equipment of shaft 1 and shaft 2. Operational interruptions in the two hoisting systems were very limited and did not affect the normal, safe operation of the HADES URL.

With the new ONDRAF/NIRAS financing agreement covering the period 2016-2020, a budget for the replacement of the shaft 1 hoisting system has been put in place. EURIDICE started preparing this project in 2016 by adding a project engineer to the team. Preparations for the start of the study phase were made by launching the public tendering procedure at the end of 2016 to appoint an engineering company by May 2017. The engineering phase got underway in the latter half of 2017, basically focusing on two main topics: shaft stability and regulations. First of all, the investigation of shaft stability is necessary so as to determine whether the shaft wall will last for another 20 years. Secondly, there needed to be a discussion with the authorities on the regulatory framework. Both topics will continue early in 2018.

A public tendering procedure for a means of communication between underground infrastructures and above-ground installations was prepared and launched at the end of 2017. Site visits, followed by tendering and contract award, will take place in the first half of 2018.

A temporary storage facility (for a few months) for germanium crystals was set up underground. These crystals were pulled and shaped by Umicore in Olen and had to be stored underground to limit above-ground exposure. Once all the crystals were ready, they were shipped to Santa Clara University in the US.

ABOVE-GROUND INSTALLATIONS AND BUILDINGS

The operations team carried out standard maintenance and necessary repairs on the installations, buildings and infrastructure in 2017.

The public tendering procedure for the replacement of the roof on the visitors' building was launched early in 2017. A contractor was subsequently appointed and the work was completed.

For the renewal of the small water treatment facilities on the EURIDICE site, a public tender was prepared and launched in 2017. The new facilities had started up by the end of 2017.

The old experimental set-up in the visitors' building to demonstrate how to insert canisters into disposal tubes has been demolished and removed to make way for core storage and/or the archives. This experiment was one of the earlier ideas about how to insert canisters, but the concept was later abandoned.

The public tendering procedure for the dismantling and removal of the ESDRED experiment was launched. The contract was awarded and by the end of 2017 the ESDRED experimental set-up had been removed from the site. Early in 2018 the contractor will pour a concrete floor and the green hangar will be rebuilt.

LICENCES

The operating licence is valid until 2024. Nothing changed in this respect in 2017.

The nuclear licence of EIG EURIDICE (issued in August 2006) was valid until 2021, but was revised in 2017 at the request of FANC. This resulted in a new licence, which was granted in July 2017 and will be valid until August 2021. All inspections and checks under this licence were carried out by BEL V.

The environmental licence of EIG EURIDICE (granted in November 2013) is valid for 20 years.

5. Quality Management

Since 2007, EIG EURIDICE has been ISO-certified according to the ISO 9001:2008 standard for Quality Management. An external audit took place on 9 March 2017. There were no major or minor non-conformities.

The current certificate was granted for the period from 22/04/2016 to 15/9/2018. Before this period expires, the Quality Management System needs to be adapted to meet the new ISO 9001:2015 standard. A Readiness Review completed by SGS at the end of 2016 identified the gaps between the current QM System and the requirements of the new standard. In December 2017 EIG EURIDICE started to adapt the current system with the support of Lloyd's Register Quality Assurance. The audit to obtain a new certificate according to the ISO 9001:2015 standard will be performed in first half 2018. In connection with this new certificate, it was decided to end the current contract with SGS. The next audit will be performed by AIB Vinçotte in first half 2018.

6. Knowledge Management

In the context of the strategic review of the future of EURIDICE, knowledge management and knowledge transfer were identified as key objectives for EURIDICE. The KM strategy for EURIDICE will be discussed and defined in consultation with both EIG members, through meetings of the newly formed R&D platform.

During 2017, a specific project was devoted to updating and restructuring EURIDICE's hard-copy archive. Svetlana Kotchetkova was hired for six months to complete this task with support from the EURIDICE team members. In the next phase, the inventory of the updated hard-copy archive needs to be finalised to ensure that the archive can be easily accessed and consulted.

Communication

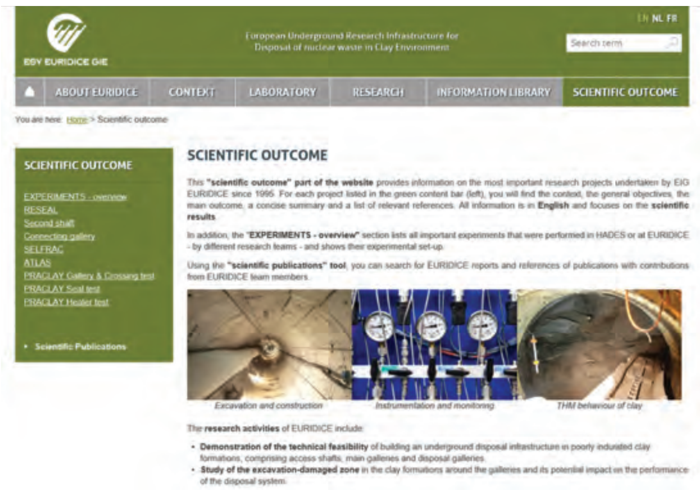
Communication about its activities is one of EIG EURIDICE's statutory tasks. The HADES underground research laboratory (URL) and the above-ground exhibition are powerful tools for explaining the concept of geological disposal and are the ideal way to present and explain the research that has been going on for the past 36 years. In addition to arranging visits to the exhibition and the URL, EURIDICE has its own website, events and publications to inform a wide audience about its activities within the context of ONDRAF/NIRAS's research programme on geological disposal.

INFORMATION PANELS HADES URL

Inside the HADES URL, 30 information panels have been installed for all experiments that have been carried out or are still ongoing. These panels give visitors a general impression of the number and variety of experiments in the underground laboratory. Scientists can use them to explain the goals and experimental set-up of each experiment when visiting the HADES URL with colleagues from other research institutes. In this way, this system of information panels contributes to knowledge transfer and record-keeping of the research activities on geological disposal in poorly indurated clay.

WEBSITE

The Scientific outcome section of www.euridice.be was finalised during the first half of 2017. This part of the website provides scientific information on the most important research projects undertaken by EIG EURIDICE since 1995. For each project, you can find the context, the general objectives, the main outcome, a concise summary and a list of relevant references. All information is in English.



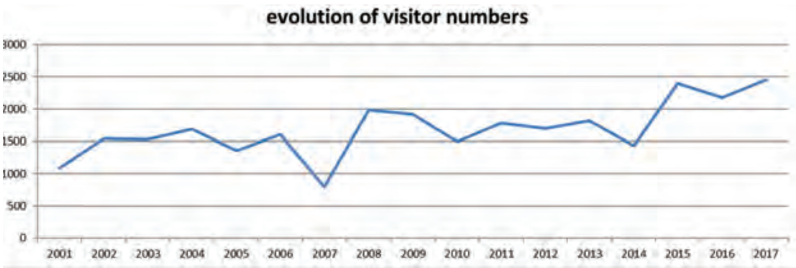
EVENTS

On Monday 29 May 2017 EIG EURIDICE organised the 21st Exchange Meeting, entitled Cement materials for radioactive waste management: new insights and current RD&D programme. The main aim of these meetings is for EURIDICE, SCK•CEN and ONDRAF/NIRAS to share information about their activities in the field of radioactive waste disposal research. As concrete is an important component in the industrial conditioning activities of ONDRAF/NIRAS's subsidiary Belgoprocess, and also in SCK•CEN's more fundamental research on the long-term evolution of concrete structures, this created a unique opportunity to exchange expertise on the subject. All presentations are available on EURIDICE's website.

VISITS

Anyone over the age of 18 can visit EIG EURIDICE and the underground research laboratory. Secondary school students can visit the permanent exhibition on geological disposal research.

In 2017 EIG EURIDICE welcomed 2,458 visitors in the course of 160 visits to the HADES URL and the above-ground exhibition on geological disposal. Of the 160 visits, 63 were for training and educational purposes and 36 involved sociocultural organisations. The remaining 61 concerned direct stakeholders of EIG EURIDICE or were arranged at the request of SCK•CEN or ONDRAF/NIRAS. 75 were Dutch-speaking, 53 English-speaking and 32 French-speaking.

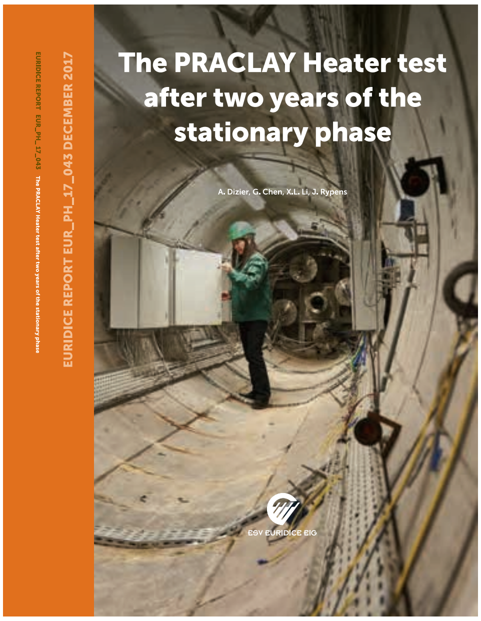


Sociocultural organisations are looked after by trained guides, who also lead visits at ISOTOPOLIS, ONDRAF/NIRAS's information centre on radioactive waste. Geological disposal experts, journalists, university students with a scientific background and key political and economic figures are given a guided tour by scientific personnel, the Communication Manager and/or the Director of EIG EURIDICE, sometimes accompanied by ONDRAF/NIRAS or SCK•CEN management.

Visit to the HADES URL

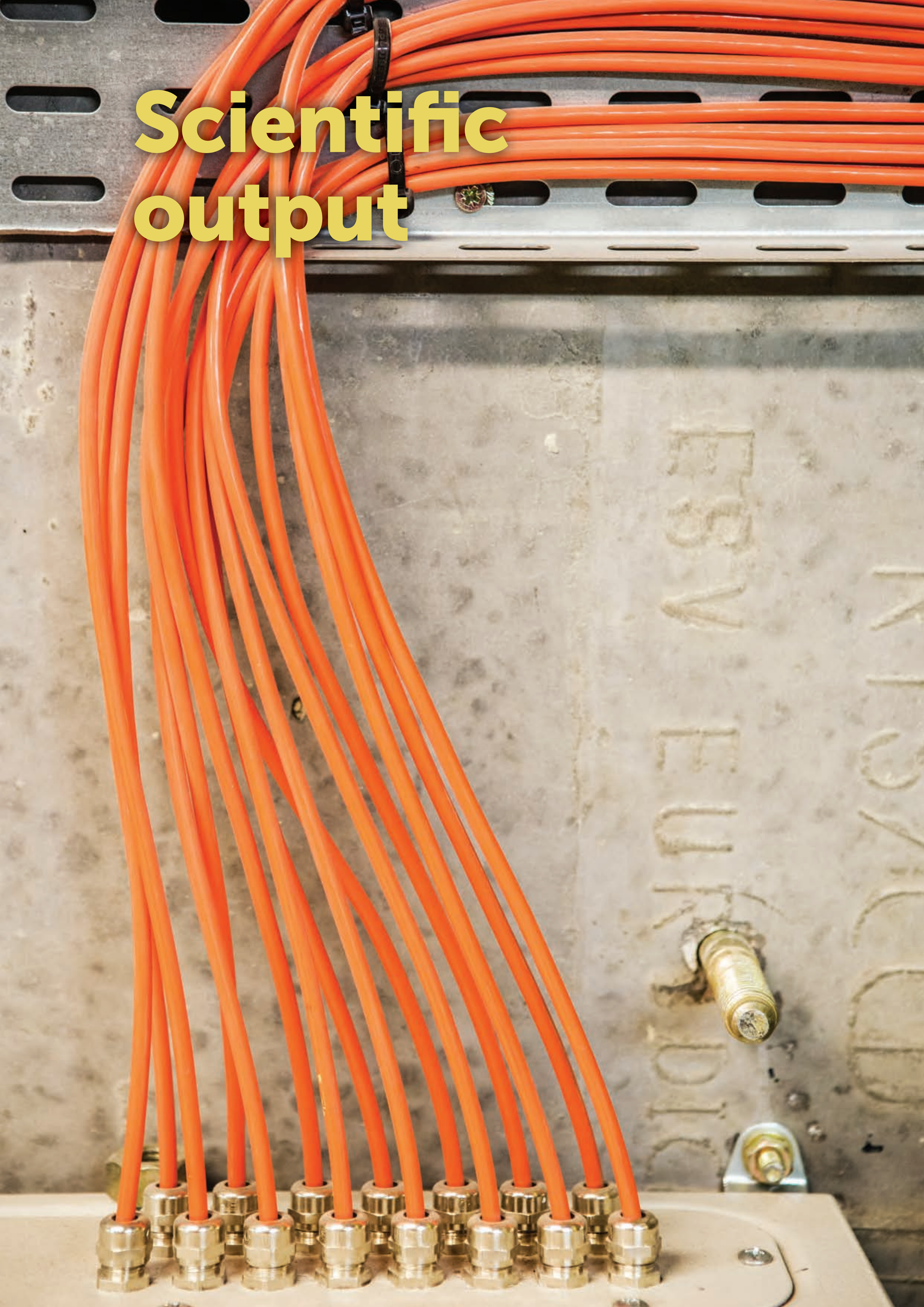
PUBLICATIONS

On 3 November 2014 the large-scale PRACLAY Heater test started in the PRACLAY gallery of the HADES URL. The target temperature of 80°C where the concrete gallery wall meets the clay was reached on 19 August 2015. This was the start of the 10-year stable heating phase at 80°C. The main measuring results of the start-up phase and the first two years of the stable heating phase have been compiled in a second technical-scientific report entitled “The PRACLAY Heater test after two years of the stationary phase”, which was finalised at the end of 2017. In this report, EURIDICE makes a first evaluation of the objectives of the experiment and devotes considerable attention to a comparison of the observations with the prior numerical predictions.



Concerning scientific communication, the EURIDICE team contributed to 16 scientific papers/ presentations in various journals and proceedings published in 2017. The list of papers is given in the next section, *Scientific output*.

Scientific output



Book and journals

Exploring fissure opening and their connectivity in a Cenozoic clay during gas injection./ González Blanco Laura, Romero Enrique, Jommi Cristina, Li Xiang Ling.
ASTMSS 2017 - Advances in Laboratory Testing and Modelling of Soils and Shales : Exploring Fissure Opening and Their Connectivity in a Cenozoic Clay During Gas Injection. ed. / Alessio Ferrari, Lyesse Laloui. Springer, 2017. p. 288-295 (Springer Series in Geomechanics and Geoengineering; Vol. 2017).

Numerical simulation of a discontinuous gallery lining's behavior and its interaction with rock./ F. Salehnia, X. Sillen, X. L. Li, R. Charlier
Int. J. Numer. Anal. Meth. Geomech. (2017) , Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/nag.2689

A solution around a backfilled cavity in a low-permeability poroelastic medium with application in in situ heating tests./ Li Yu, Guangjing Chen, Eef Weetjens
International Journal for Numerical and Analytical Methods in Geomechanics Vol 41(1):3-29

Geological disposal of nuclear waste./ Xiangling Li (as guest editor)
a special issue for the "Journal of Rock Mechanics and Geotechnical Engineering", Volume 9, Issue 3, Pages 383-574, June 2017.

Effects of temperature and thermally-induced microstructure change on hydraulic conductivity of Boom Clay ./ W.Z. Chen, Y.S. Ma, H.D. Yu, F.F. Li, X.L. Li, X. Sillen
Journal of Rock Mechanics and Geotechnical Engineering, Volume 9, Issue 3, Pages 383-395, June 2017.

Public report

The PRACLAY Heater test after two years of the stationary phase./ Dizier A., Chen G., Li X.L., Rypens J. 2017, Euridice report EUR_PH_17_043 December 2017

Conference lectures and presentations

The PRACLAY Heater Test at URL HADES: Results after 3-year heating. / Chen Guangjing, Dizier Arnaud, Leysen Jef, Verstricht Jan, Troullinos Ioannis, Li Xiang Ling, Sillen Xavier, Bastiaens Wim, Levasseur Séverine 2017. 7th International Conference on Clays in Natural and Engineered Barriers for Radioactive Waste Confinement, Davos, Switzerland.

The large scale in situ PRACLAY seal test in Belgian URL HADES for HLW disposal./ X.L. Li, G.J. Chen, A. Dizier, J. Leysen, I. Troullinos, J. Verstricht, S. Levasseur, X. Sillen
Keynote lecture in the 4th International Symposium on Unsaturated Soil Mechanica and Waste Disposal , July 14-16 , 2017 , Shanghai, China

Poster in conference

In-situ "PRACLAY Seal Test" in URF HADES, Belgium./ G.J. Chen, A. Dizier, J. Verstricht, I. Troullinos, J. Leysen, XL. Li , X. Sillen, S. Levasseur
2017. poster session presented at The first BEACON international scientific workshop on Mechanical Properties of Bentonite Barriers, 18-21 June 2017, Kaunas, Lithuania

Gas migration in deep argillaceous rock formations from experimental results to modelling./ L. Gonzalez-Blanco, E. Romero, X. Sillen, XL. Li, P. Marschall
2017. Poster session presented at 7th International Conference on Clays in Natural and Engineered Barriers for Radioactive Waste Confinement, Davos, Switzerland.
Research output: Contribution to conference › Poster

Thermal properties of a deep eocene clay formation. Direct measurements vs back-analysis results./ E. Romero, N. Sau, A. Lima, H. Van Baelen, X. Sillen, X. Li
2017. Poster session presented at 7th International Conference on Clays in Natural and Engineered Barriers for Radioactive Waste Confinement, Davos, Switzerland.

Temperature effect on the drained creep behavior of boom clay./WZ Chen, Z Gong, YS Ma, HD Yu, XL Li
2017. Poster session presented at 7th International Conference on Clays in Natural and Engineered Barriers for Radioactive Waste Confinement, Davos, Switzerland.

Laboratory investigation of the undrained behavior of boom clay under loading – unloading paths./ HD Yu, WZ Chen, Z Gong, YS Ma, XL Li, GJ Chen
2017. Poster session presented at 7th International Conference on Clays in Natural and Engineered Barriers for Radioactive Waste Confinement, Davos, Switzerland.

Modelling of Drying Shrinkage in Concrete; a Multiscale Pore-network Approach./ Babaei S., Seetharam S., Muehlich U., Areias L., Steenackers G., Craeye B.
2017. Poster session presented at PhD Day, Mol, Belgium.

Evolution of Boom Clay in-situ permeability around the Connecting and PRACLAY galleries in the HADES URF./ Chen Guangjing, Dizier Arnaud, Li Xiang Ling; Verstricht Jan, Bastiaens Wim, Sillen Xavier, Levasseur Séverine
2017. Poster session presented at 7th International Conference on Clays in Natural and Engineered Barriers for Radioactive Waste Confinement, Davos, Switzerland.

A systematic assessment of the sensor performance in long-term experimental set-ups in the URL HADES./J. Verstricht, L. Areias, I. Troullinos, D. Leonard , M. Van Geet
2017. Poster session presented at 7th International Conference on Clays in Natural and Engineered Barriers for Radioactive Waste Confinement, Davos, Switzerland.

List of accronyms

ANDRA	Agence Nationale pour la Gestion des Déchets Radioactifs (FR)
BDT	Below Drilling Table
BGL	Below Ground Level
CAS	Chinese Academy of Science
CIMNE	Centro Internacional de Métodos Numéricos en Ingeniería (ES)
CLIPEX	CLay Instrumentation Programme for the EXtension of an underground research laboratory
EBS	Engineered barrier system
EC	European Commission
EDZ	Excavation-damaged zone
ESDRED	Engineering Studies and Demonstration of Repository Designs
FANC	Federal Agency for Nuclear Control (BE)
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (DE)
GSIS	GeoScientific Information System
HADES	High-Activity Disposal Experimental Site
IRMM	Institute for Reference Materials and Measurements (BE)
IRSM	Institute of Rock and Soil Mechanics (China)
ISOTOPOLIS	ONDRAF/NIRAS's information centre about radioactive waste management, located in Dessel
Modern2020	Development and Demonstration of monitoring strategies and technologies for geological disposal (within the framework of the Horizon 2020 Euratom Work Programme)
MONA	Mols Overleg Nucleair Afval (local citizen platform on nuclear waste issues in Mol)
NAGRA	Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (CH)
ONDRAF/NIRAS	Belgian Agency for Radioactive Waste and Enriched Fissile Materials (BE)
OPHELIE	On-surface Preliminary Heating simulation Experimenting Later Instruments and Equipment
POP	Programme Committee for Underground Experiments
SAC	Scientific Advisory Committee
SCK•CEN	Belgian Nuclear Research Centre (BE)
SELFRAC	Fractures and self-healing within the excavation-disturbed zone in clays
STORA	Studie en Overleggroep Radioactief Afval in Dessel (local citizen platform on nuclear waste issues in Dessel)
TAW	Tweede Algemene Waterpassing (Belgian reference towards sea level)
THM	Thermo-hydro-mechanical
THMC	Thermo-hydro-mechanical-chemical
UPC	Universitat Politècnica de Catalunya (ES)
URL	Underground research laboratory

ESV EURIDICE EIG

EIG EURIDICE is an Economic Interest Grouping involving the Belgian Nuclear Research Centre SCK•CEN and the Belgian Agency for Radioactive Waste and Enriched Fissile Materials (ONDRAF/NIRAS). It manages the HADES underground research facility and carries out safety and feasibility studies for the disposal of high-level and/or long-lived radioactive waste in a clay host rock.

Boeretang 200
2400 Mol
tel. 014 33 27 84
fax 014 32 37 09
www.euridice.be