

2018

Activity Report



ESV EURIDICE EIG

2018

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Approved by:

Hildegarde Vandenhove, Board of Governors

Marc Demarche, Chairman of the Board

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General foreword

Marc Demarche, Chairman of the Board of EIG EURIDICE

Dear reader,

EIG EURIDICE is the Economic Interest Grouping between ONDRAF/NIRAS and SCK•CEN. It is responsible for managing and operating the HADES underground research laboratory (URL), carrying out research and development activities for the geological disposal of radioactive waste in deep clay formations and communicating its activities. This Activity Report provides a comprehensive overview of the main developments and results relating to the statutory tasks of EIG EURIDICE in 2018. The scientific research work is divided into two parts. Part 1 is the most extensive and focuses on the activities within the framework of the ONDRAF/NIRAS research programme for geological disposal. Part 2 zooms in on EURIDICE's activities in support of ONDRAF/NIRAS's programme for the surface disposal of low-level radioactive waste.

In 2018 the strategic review of the operation of EIG EURIDICE and its vision for the future was largely completed in consultation with its constituent members. Proposals to amend the Statutory Rules and Internal Rules and Regulations of EIG EURIDICE were then submitted to SCK•CEN and ONDRAF/NIRAS for approval by the two Boards of Management, expected in early 2019. It is the intention of both members to continue the cooperation through the EIG until 2045 and to reach further agreements about the future use of the HADES underground laboratory by both members. Through the newly established RD&D platform, the members, together with the EURIDICE team, will discuss and determine the direction of future research in HADES. The introduction of the position of a team manager makes it possible to coordinate the very different activities of EIG EURIDICE on a daily basis and thus to further improve its operation.

In order to ensure the safe use of the HADES underground laboratory for such a long period of time, EIG EURIDICE is preparing for the renovation of shaft 1, which dates back to the early 1980s. In 2018 the stability of the concrete wall of the shaft was thoroughly checked and assessed positively. The hoisting system and all the utility lines in the shaft will be refurbished. In the course of 2018 EURIDICE, with the help of an external engineering office, prepared and launched the public procurement contracts for the design and construction of the renovation of shaft 1. The various lots are scheduled to be awarded in mid-2019.

Since 1995 the PRACLAY project, as part of ONDRAF/NIRAS's RD&D programme on geological disposal, has been a top priority for EIG EURIDICE. The large-scale PRACLAY Heater test, carried out in the PRACLAY gallery of the HADES URL, is the final phase of this project. Its purpose is to ensure, on a scale representative of an actual high-level waste repository, that the heat emitted by this type of waste does not adversely affect the containment properties of the clay. 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.

The heating phase continued in 2018, successfully concluding the third year of heating at 80°C. The numerous measuring devices and sensors in and around the PRACLAY gallery monitor all important aspects of the Heater test and its evolution over time (PRACLAY gallery, concrete lining, seal structure, clay). All scientific findings and results obtained since the start of the Heater test show that the temperature rise in the clay does not significantly alter its structural integrity or its ability to act as an effective barrier to a disposal system. These findings and results generally confirm the "numerical predictions", which 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](#).

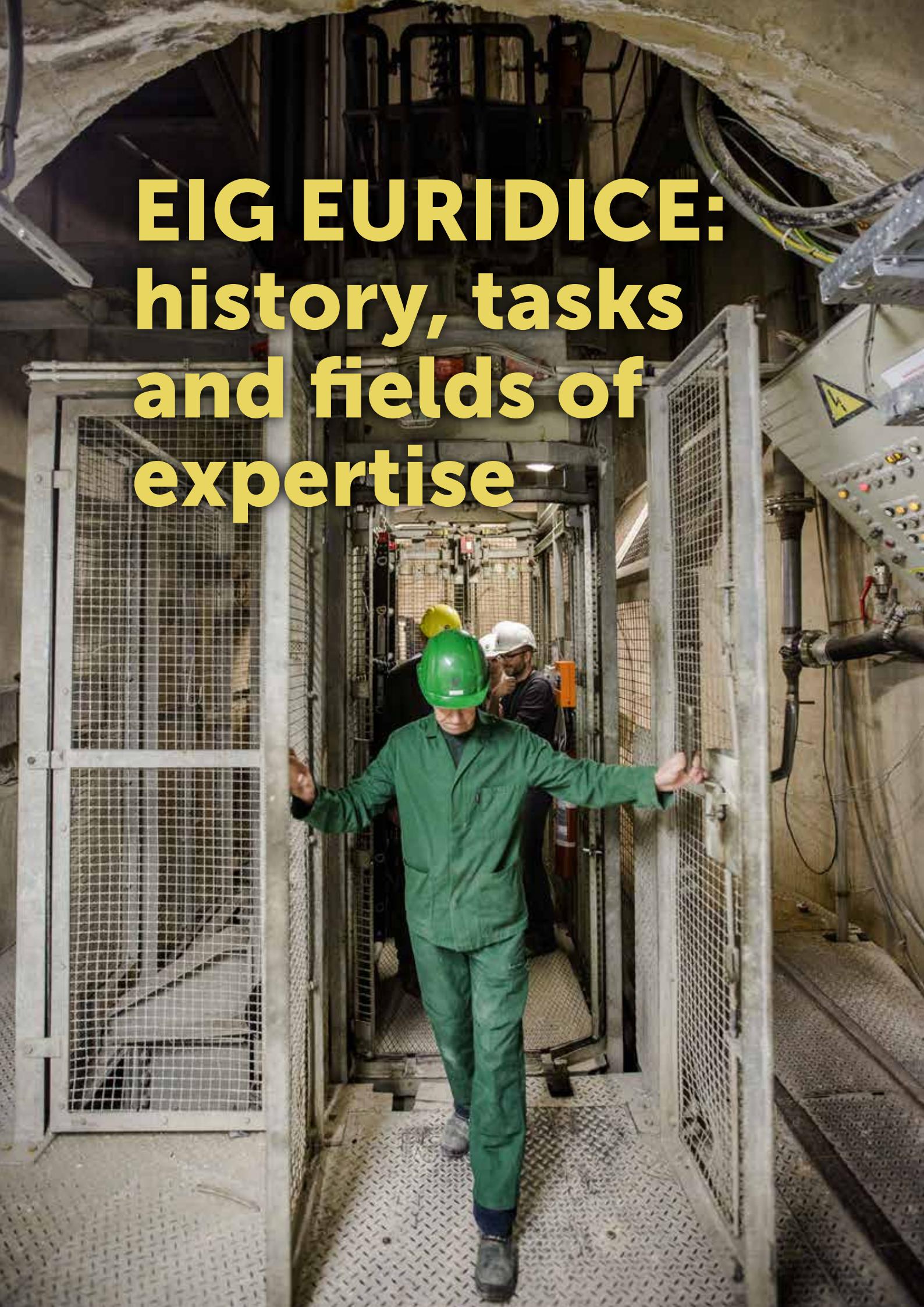
The PRACLAY Heater test is not only a success in terms of its positive test results. The many years of preparation and the 10 year heating phase offer an excellent opportunity to ensure continuity of knowledge and expertise within the organisation. To share this knowledge, a wide audience is regularly kept informed about how the test is progressing through newsletters, external reports and numerous presentations. In the course of 2018 EURIDICE prepared a number of reports with a detailed evaluation of the scientific findings and of the performance and reliability of the measuring instruments since the start of the Heater test in November 2014. Publication is scheduled for the first half of 2019.

In 2018 EURIDICE received more than 3,000 visitors, which is an all-time record. Much of the increase compared to 2017 is due to a larger number of secondary schools visiting the above-ground exhibition. Specifically for these above-ground school visits, EURIDICE, together with an external partner, developed a more interactive approach in 2018 in the form of a game, *De Bergemeesters*, which will be launched in the course of 2019.

2019 promises to be an exciting and unique year. The main event of the year will undoubtedly be the replacement of the hoisting system of shaft 1. The work will temporarily have a major impact on the operation and accessibility of the underground laboratory. However, it is a necessary "rejuvenation" that will prepare HADES to welcome visitors and scientists for many years to come. I am very much looking forward to that.

Marc Demarche, Chairman of the Board of EIG EURIDICE

EIG EURIDICE: history, tasks and fields of expertise

A photograph showing a man in green work clothes and a yellow hard hat walking through a industrial facility. He is walking towards the camera, with his arms slightly outstretched. In the background, another person wearing a white hard hat is visible. The facility has metal railings and various industrial equipment.

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 PRACTAY 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 more than 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 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.

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 2013 ONDRAF/NIRAS finalised its RD&D plan on geological disposal (NIROND-TR 2013-12 E), describing the main achievements and future challenges. This RD&D plan defines the guidelines for EIG EURIDICE's RD&D activities. The next milestones in the national programme will largely depend on the timing and nature of the policy decision that needs to be taken following the 2011/70/EURATOM Council Directive establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste.

EIG EURIDICE's scientific activities in 2018 focused on following up the PRACLAY Heater test. Since the temperature at the interface between the concrete lining and the clay reached the target of 80°C in August 2015, the power of the heating system has been systematically adjusted to keep the temperature constant at 80°C (stationary heating phase). At the start of 2018 a second report was distributed 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. In addition to the work related to the PRACLAY Heater test, a great deal of effort went into assessing sensor performance in the experimental set-ups in the HADES URL. The first project under CLIPEx, which started in 2015, was finalised in 2018. A second project, focusing on the sensor performance of PRACLAY, began in 2018.

This Activity Report gives an overview of the main observations regarding the PRACLAY Heater test since switching on the heating system on 3 November 2014 up until the end of 2018, 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.

EIG EURIDICE today



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 2018 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 Vandenhoove, Director of the Environment, Health and Safety Institute of SCK•CEN

Responsibility for day-to-day management of EURIDICE lies with the **Director**, who is appointed by ONDRAF/NIRAS. In the course of 2018 a new management position of "team manager" was created to support the Director. The **team manager** is appointed by SCK•CEN.

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 2018, 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 2018, formal proposals were finalised and submitted to SCK•CEN and ONDRAF/NIRAS for approval by their respective Board of Management, expected in the first half of 2019:

- The new Statutory Rules of EIG EURIDICE;
- The new Internal Rules and Regulations of EIG EURIDICE;
- A proposed agreement on the establishment of a building lease and a proposed agreement regarding pre-emptive rights, by amending the existing agreements in these areas;
- A proposed collaboration agreement between EIG EURIDICE and its constituent members SCK•CEN and ONDRAF/NIRAS, replacing the agreement on the secondment of employees by the two members.

With the proposal of new **Statutory Rules** for EIG EURIDICE the most important changes will be:

- The extension of the lifetime of the EIG from 2025 until 2045;
- The emphasis in the statutory tasks on knowledge management and enhancing the scientific value of the RD&D activities of EIG EURIDICE and in the HADES URL;
- The introduction of the position of team manager, supporting the Director in the day-to-day management of EIG EURIDICE and its team;

The new Statutory Rules and Internal Rules and Regulations introduce the three advisory bodies to the Board of the EIG: (1) the consultative committee on safety, health, environment & security, (2) the consultative committee on communication and (3) the consultative platform on RD&D. These bodies will support EIG EURIDICE in its activities and will facilitate consultation and collaboration with its constituent members in the respective fields. They will be composed of representatives of the constituent members, a representative of EIG EURIDICE, and the Director and/or Team Manager of EIG EURIDICE. The committees will identify the objectives and priorities of EIG EURIDICE in each of the three fields. They will meet on a regular basis and report to the [Board of Directors](#) of EIG EURIDICE.

EIG EURIDICE has been ISO-certified according to the ISO 9001 standard for Quality Management since 2007. In 2018 the Quality Management System was adapted, with the support of Lloyd's Register Quality Assurance, to meet the new ISO 9001:2015 standard. The external audit was performed by AIB Vinçotte and took place on 29 June and 2 July. The new certificate according to the 2015 standard was granted for the period from 24 September 2018 to 23 September 2021.

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

Team Manager:

Mieke De Craen

Scientific team:

Xiangling Li – responsible for RD&D

Lou Areias - scientific collaborator (retired in January 2018)

Arnaud Dizier - scientific collaborator

Guangjing Chen - scientific collaborator

Ioannis Troullinos - scientific collaborator

Jan Verstricht - scientific collaborator

Wim Bastiaens - scientific collaborator

Technical team:

Jef Leysen – responsible for operations & safety

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

Responsible for communications:

Jan Rypens

RD&D Part 1

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



1. PRACTAY "Demonstration & confirmation experiments"

1.1. Introduction: the PRACTAY project

One of the aims of EIG EURIDICE is the development and execution of the PRACTAY 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 PRACTAY project consists of several sub-projects and experiments. Together, these are referred to as the PRACTAY "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 PRACTAY 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: PRACTAY IN-SITU (meaning "in HADES") and PRACTAY ON-SURFACE experiments.

PRACTAY 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 PRACTAY 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 PRACTAY 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 PRACTAY Heater test is discussed in Section 1.2.

For this purpose, part of the PRACTAY 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. This means that the test is representative of the conditions that would be expected in a high-level waste repository. After the construction of the PRACTAY 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 PRACTAY Heater test 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 PRACTAY gallery, and compared with the predictions made by modelling. A second report was written in 2017 (EUR_PH_17_043) and distributed in 2018, 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 PRACTAY Heater test.

By the end of 2018 the PRACTAY Heater test had been running for more than four years. The experimental set-up is still working perfectly. Using the new data generated in the Heater test, EIG EURIDICE scientists continue to improve the interpretation of the in-situ measurements and understanding of the THM behaviour of the Boom Clay through in-situ testing and numerical modelling.

PRACTAY 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 2018.

1.2. PRACTAY IN-SITU: the Heater test

1.2.1. Test set-up

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

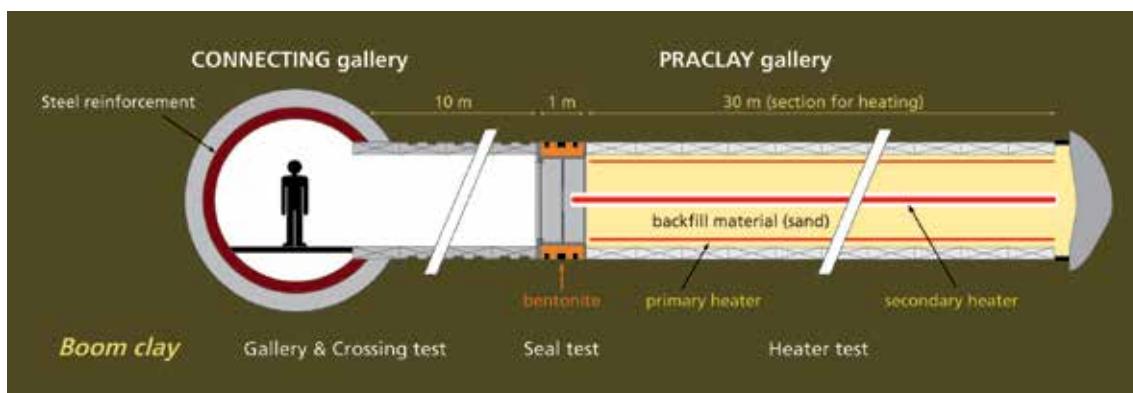


Figure 2 – Design of the PRACTAY experiment

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.

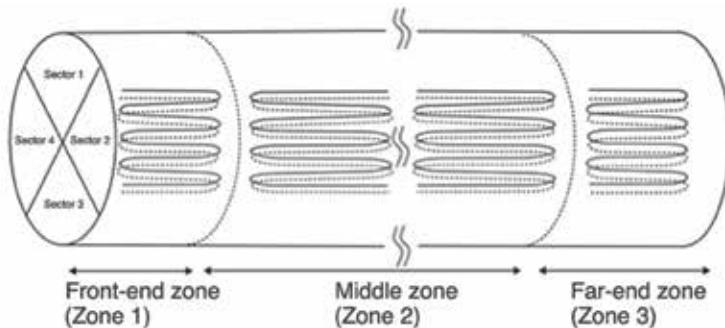


Figure 4 - The primary heating system is composed of three zones, each divided into four sections

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. The secondary heater will only be used should the primary heater fail. Since the start of the Heater test on 3 November 2014, only the primary heater has been used.

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).

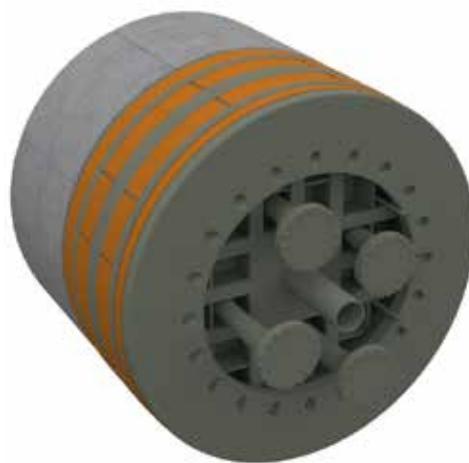


Figure 5 - 3D view of the seal with a central steel cylinder and an annular ring of bentonite (orange) against the clay

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, so as not to re-damage the surrounding Boom Clay. The minimum swelling pressure before switch-on was set at 2.5 MPa 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 ($\approx 10^{-12}$ 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 (i.e. voids left after the installation of the bentonite blocks) and the interaction with the Boom Clay. An initial dry density of 1.8 tonnes/m³ 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).

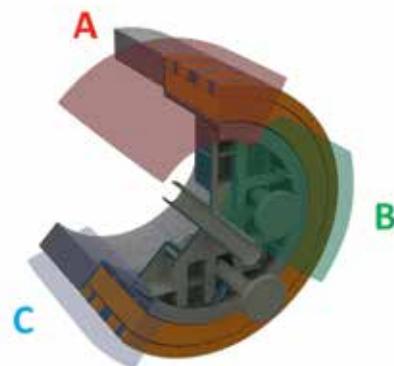


Figure 6 - Various instruments inside the bentonite, grouped into sections A, B and C

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 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.

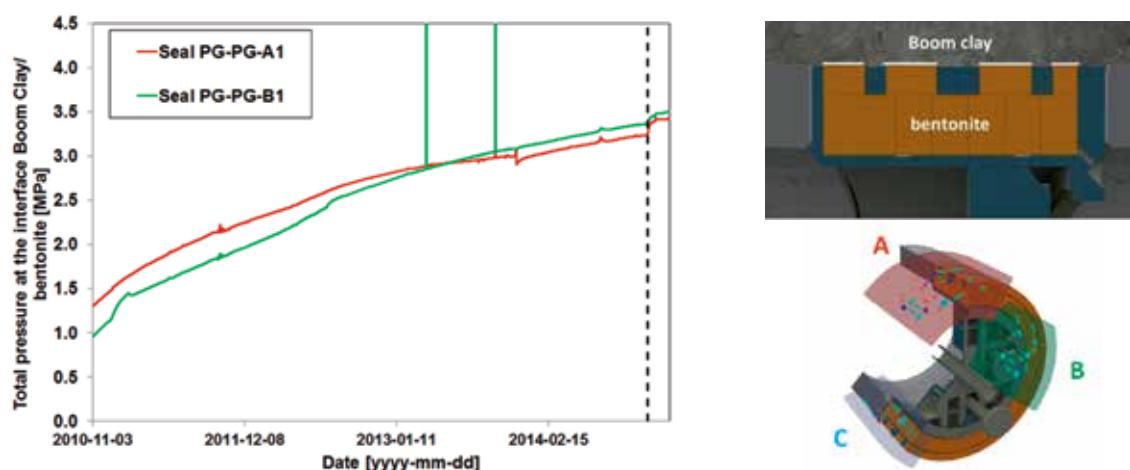


Figure 7 - Radial stresses measured at the interface between the bentonite and the Boom Clay sidewall (white line in insert), for sections A, B and C. The vertical dashed line marks the date of the switch-on.

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, steering 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 2018

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 predictive 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 evolutions 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.

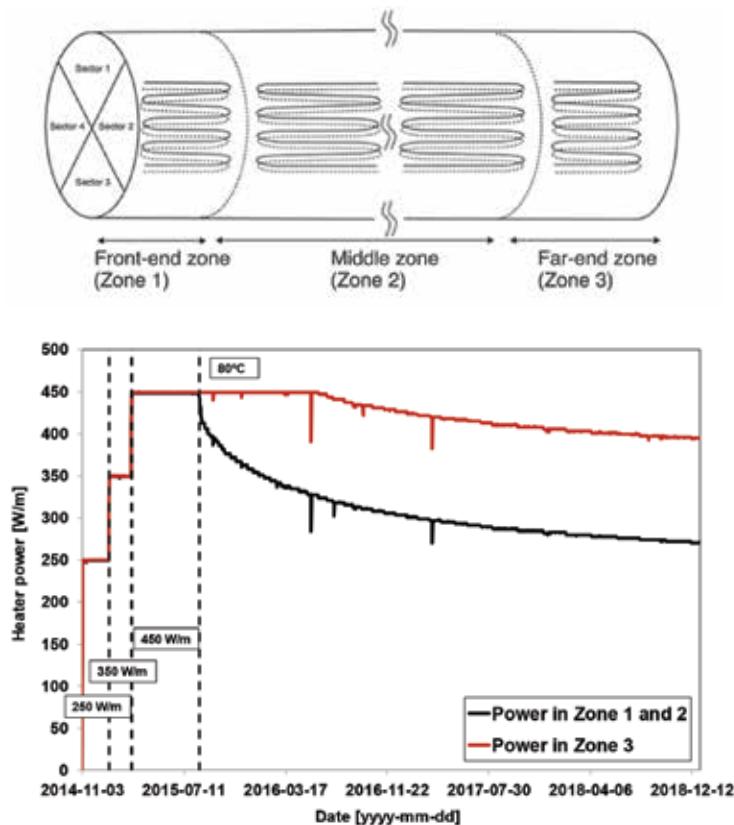


Figure 8 - Evolution of the power in watts per metre (W/m) in the three zones. The power in Zones 1 and 2 was decreased once the temperature in Zone 2 reached 80°C (measured by T_{int_1}). The power in Zone 3 was decreased with a delay of a couple of months once Zone 3 reached 80°C (measured by T_{int_2}).

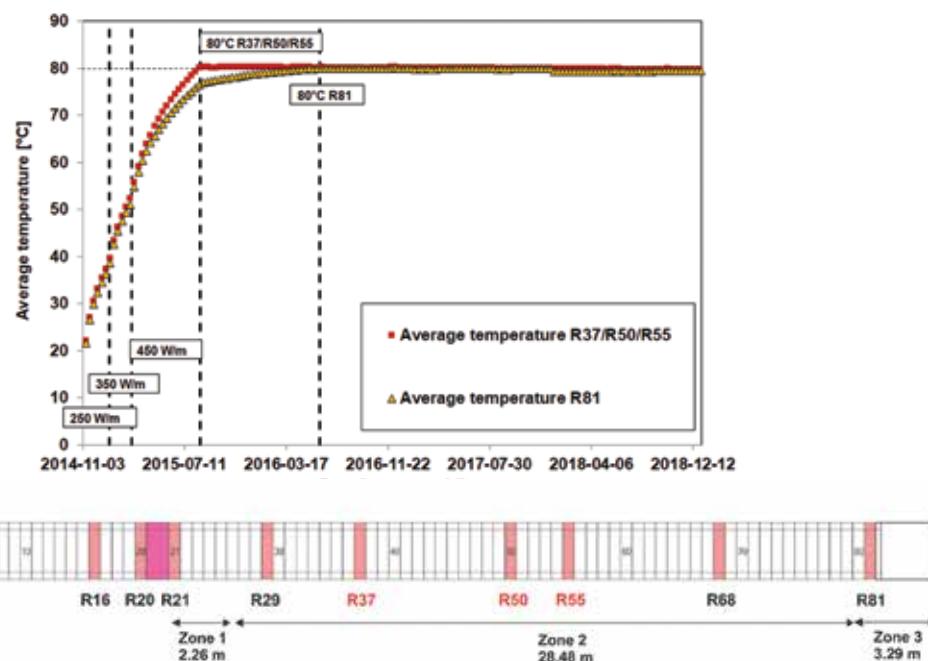


Figure 9 - Average temperature evolution measured using the extrados sensors in R37, R50 and R55 (T_{int_1}) and R81 (T_{int_2})

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.

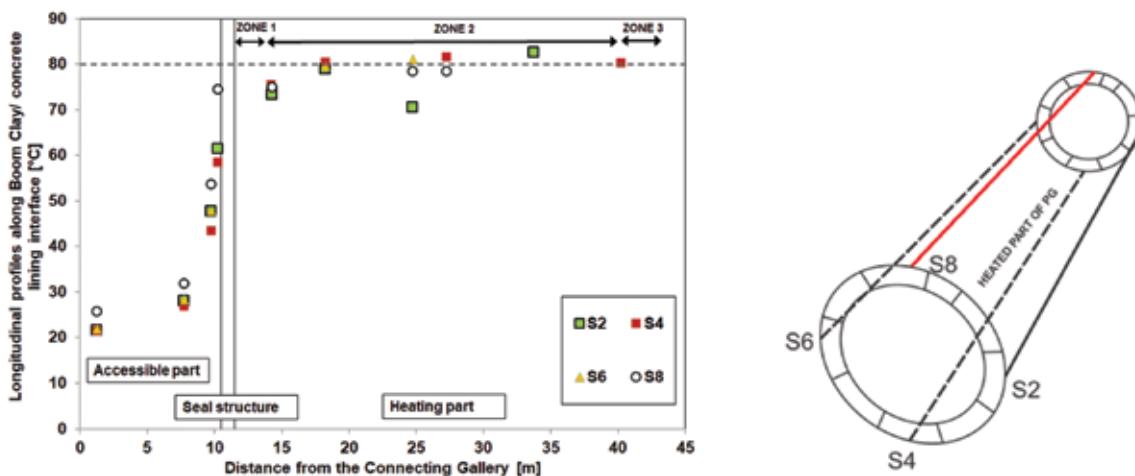


Figure 10 - Longitudinal profiles of the temperature along the extrados of the PRACTLAY gallery (end 2018)

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 concrete lining and the Boom Clay), an excess pore water pressure in the system is induced inside the PRACTLAY gallery. This rise in pore water pressure in the backfilled part of the PRACTLAY 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 into 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 sand backfill material, the pore water pressure inside the backfilled part of the PRACTLAY gallery is uniform.

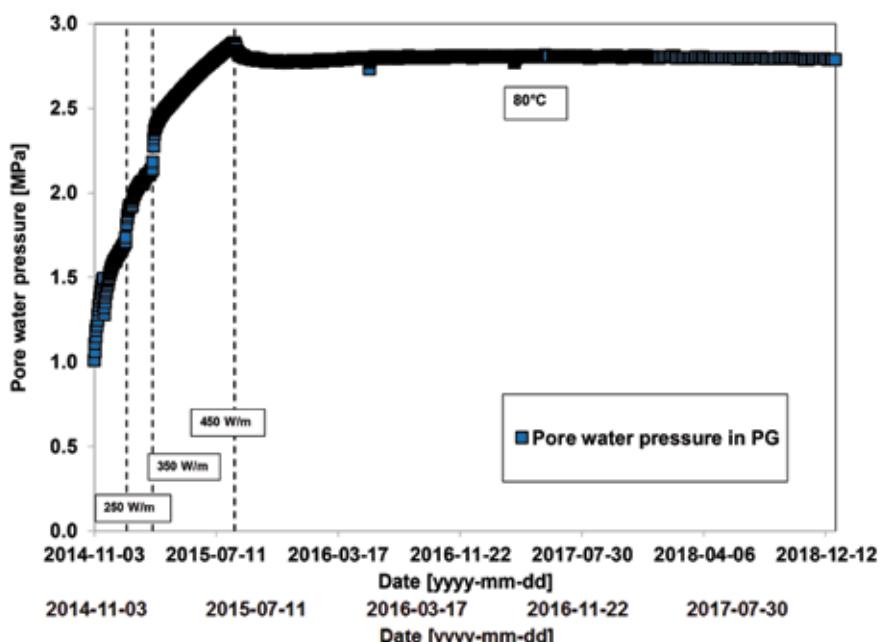


Figure 11 - Pore water pressure evolution in the backfilled part of the PRACTLAY gallery

BOOM CLAY RESPONSES

Porous media with low permeability, such as 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 (water) in the clay. 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).

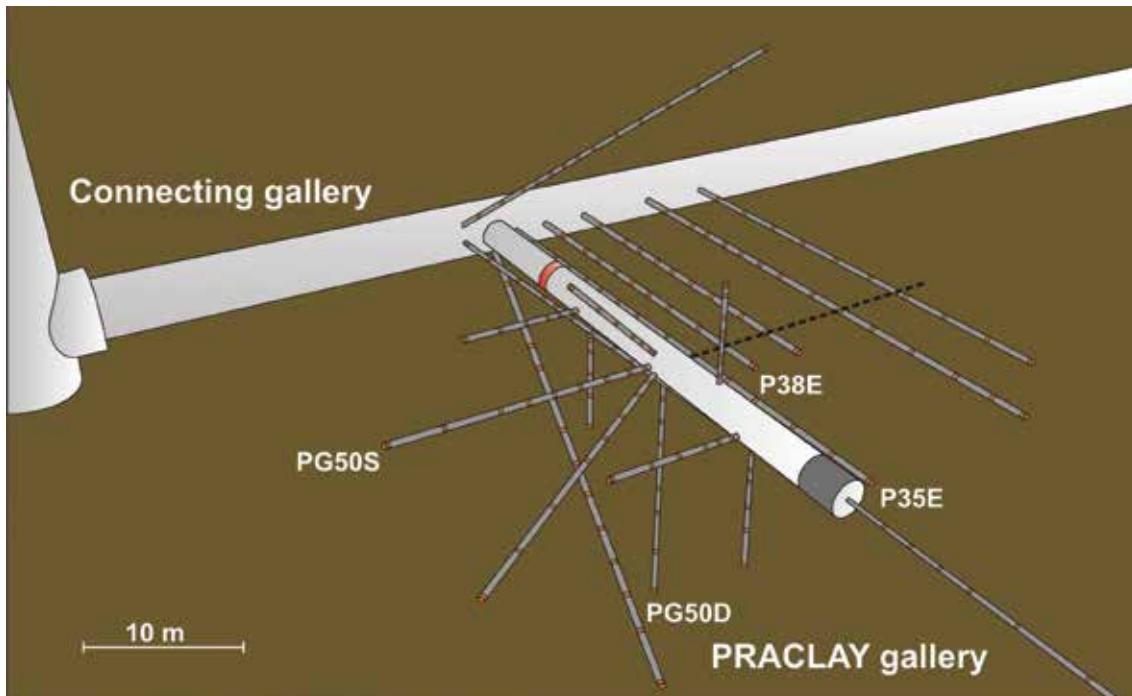


Figure 12 - 3D view of the instrumented boreholes from the PRACLAY gallery and the Connecting gallery

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 by the dashed line in Figure 12) is illustrated in Figure 14.

It was observed that, by the end of 2018, the thermally affected zone had extended to a distance of more than 15 m into the Boom Clay in both horizontal and vertical directions (Figure 13a and Figure 14a). At any 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 by conduction 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 concrete 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). By comparing the pore water pressure profiles at a distance of around 5 m from the gallery intrados in 2017 and 2018 (Figure 14b), it can be observed that the peak of maximum excess pore water pressure in the Boom Clay was reached in 2017. Since that time, the excess pore water pressure has been dissipating into the surrounding environment. The measurements from horizontal boreholes drilled from the Connecting gallery indicate clearly that the hydraulically affected zone due to heating had extended more than 20 m at the end of 2018 (Figure 14 b).

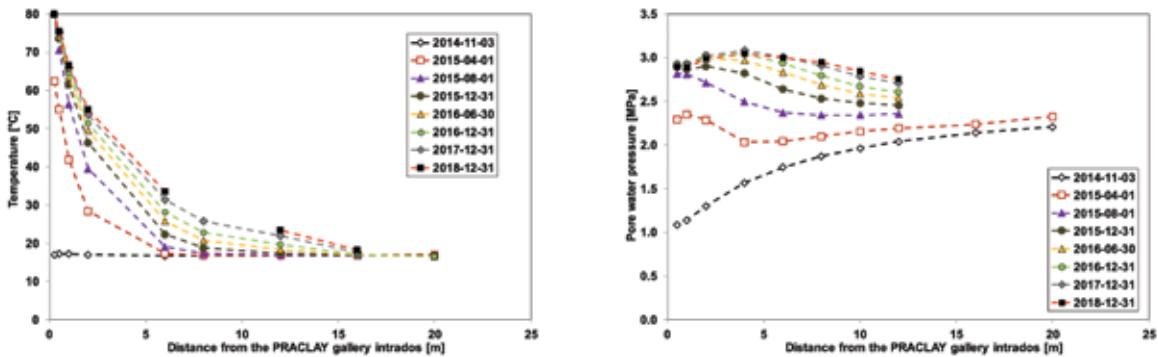


Figure 13 - Temperature and pore water pressure profiles in the vertical direction at the middle section of the heated part of the PRACLAY gallery (along borehole PG50D)

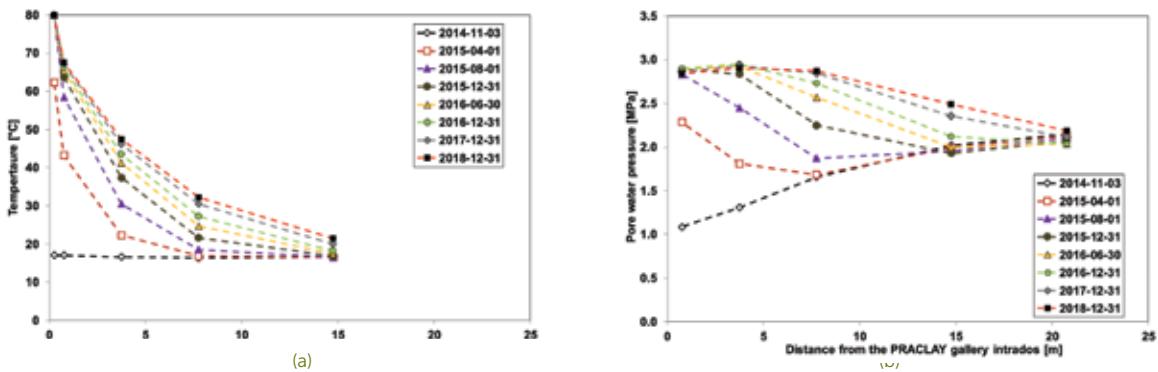


Figure 14 - Temperature and pore water pressure profiles in the horizontal direction at the middle section of the heated part of the PRACLAY gallery (measured from boreholes drilled from the Connecting gallery)

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 2 m from the axis of the PRACLAY gallery (Figure 15c). 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.

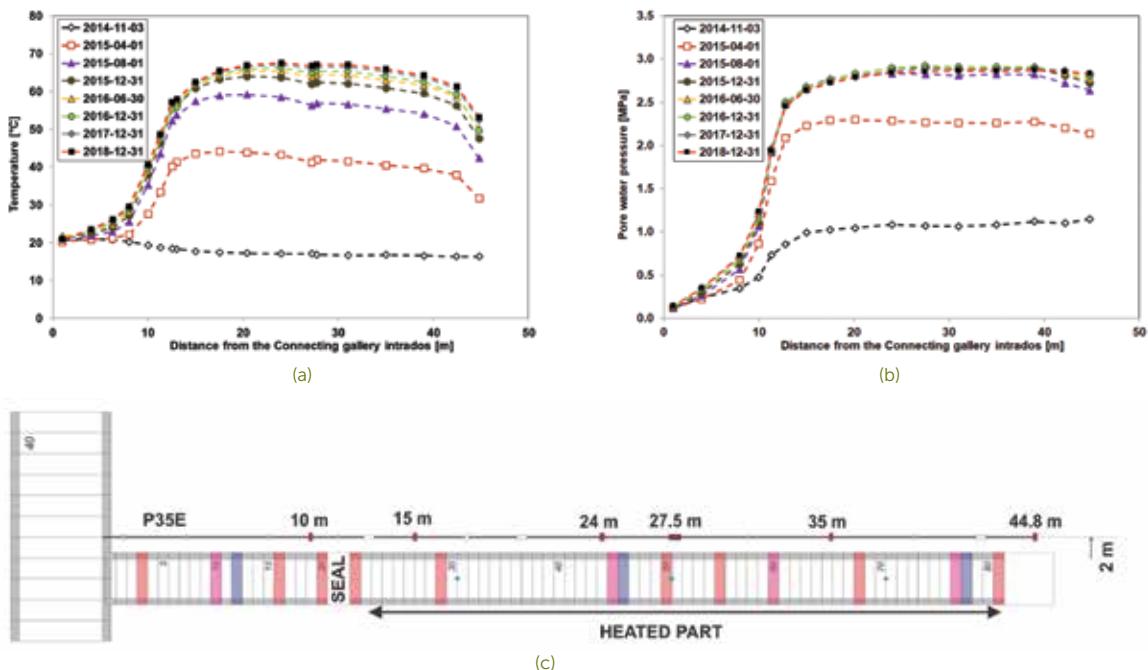


Figure 15 - Temperature and pore water pressure profiles in P35E

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 filters surrounding the heated zone of the gallery, which is also closest to the pore water pressure measured inside the PRACLAY gallery. If we look at the evolution of the profiles in more detail, the pore water pressure measured in these filters has shown a slight decrease since the end of 2016. This is consistent with what was observed previously. The peak in the pore water pressure was reached last year, marking the start of the dissipation of the pressure into the surrounding environment. This phenomenon was expected from the predictive modelling.

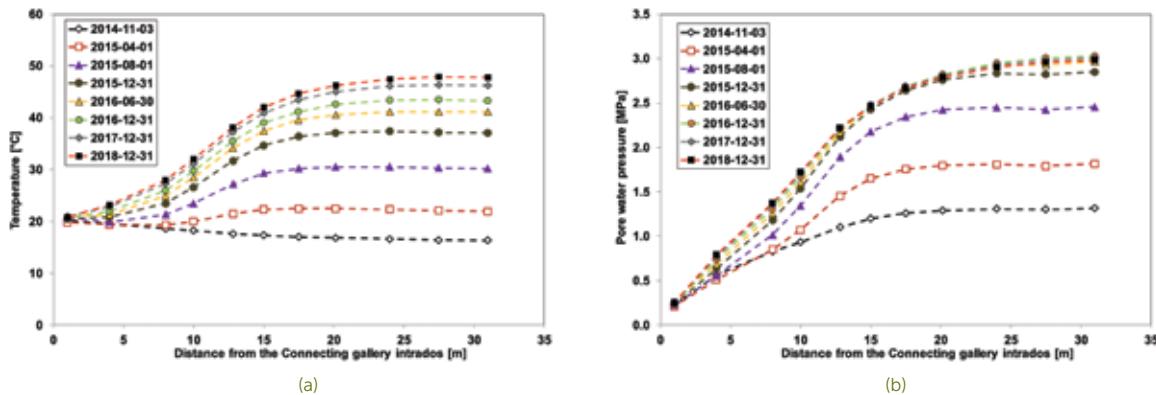


Figure 16 - Temperature and pore water pressure profiles in P38E

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 contact zone between the bentonite ring and the Boom Clay is well sealed and has low permeability. Moreover, the pore water pressure inside the PRACLAY gallery is maintained as expected due to fact that the seal is performing well.

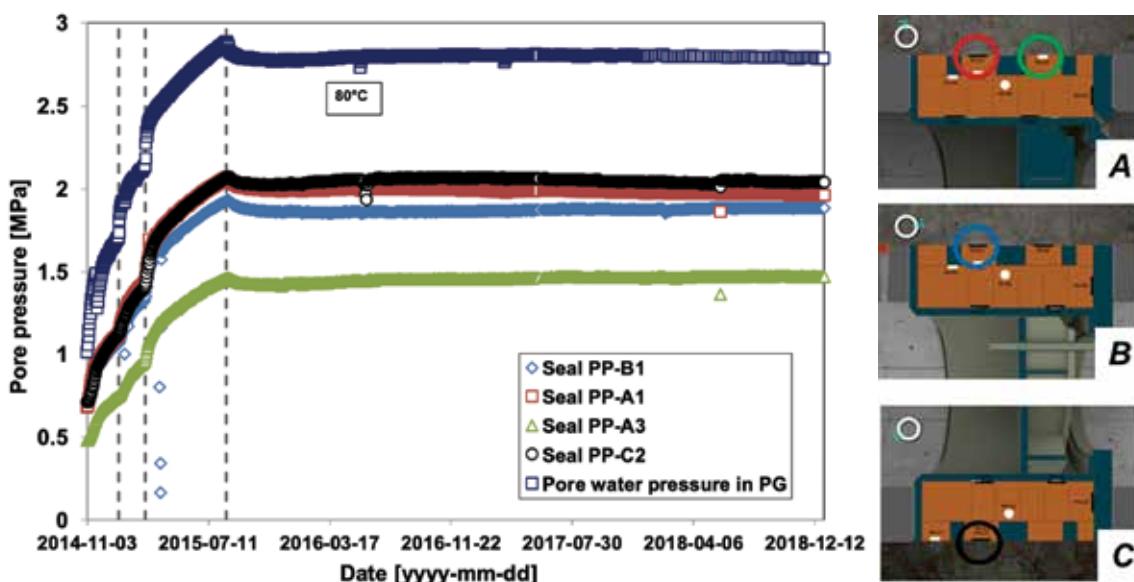


Figure 17 - Evolution of the pore water pressure at the Boom Clay/bentonite interface

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 has been maintained. However, it can be observed that the pore water pressure measured from piezometer Ring-21-S8 tends to decrease smoothly. There were no explanations for this decrease at the time of writing this report.

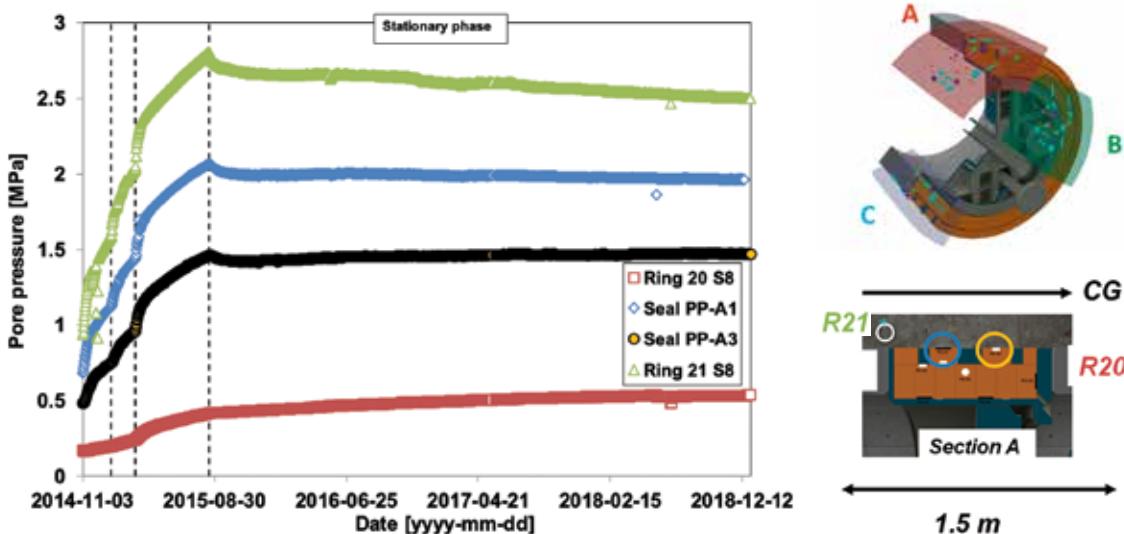


Figure 18 - Pore water pressure evolution at the Boom Clay/concrete lining and Boom Clay/bentonite interfaces

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 more than 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.

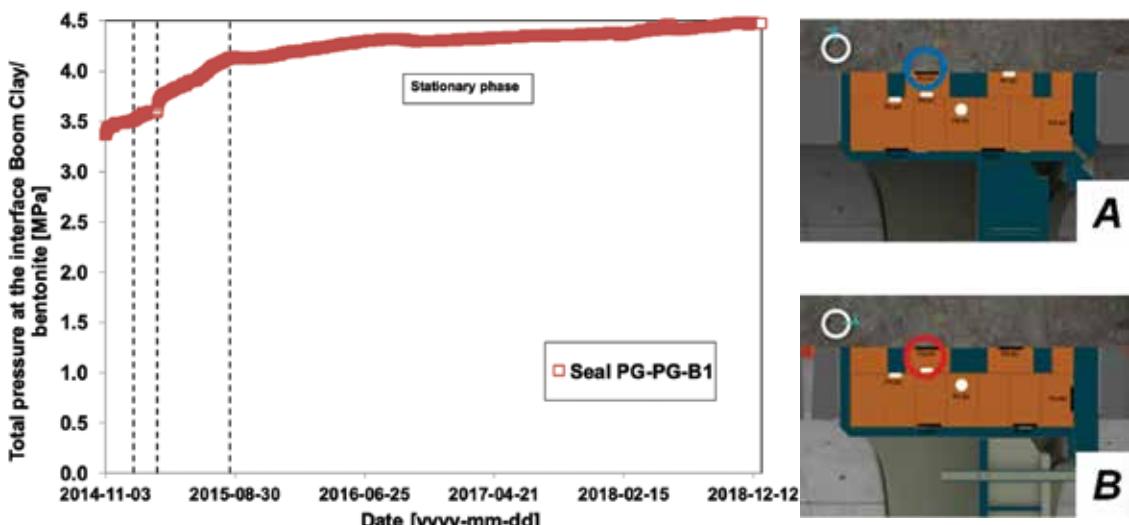


Figure 19 - Total pressure at the Boom Clay/bentonite interface in sections A and B

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. The measured displacement remained quite constant and an average value of 12 mm over the three monitored prisms was observed at the end of 2018, without any impact on the stability and the functioning of this seal structure.

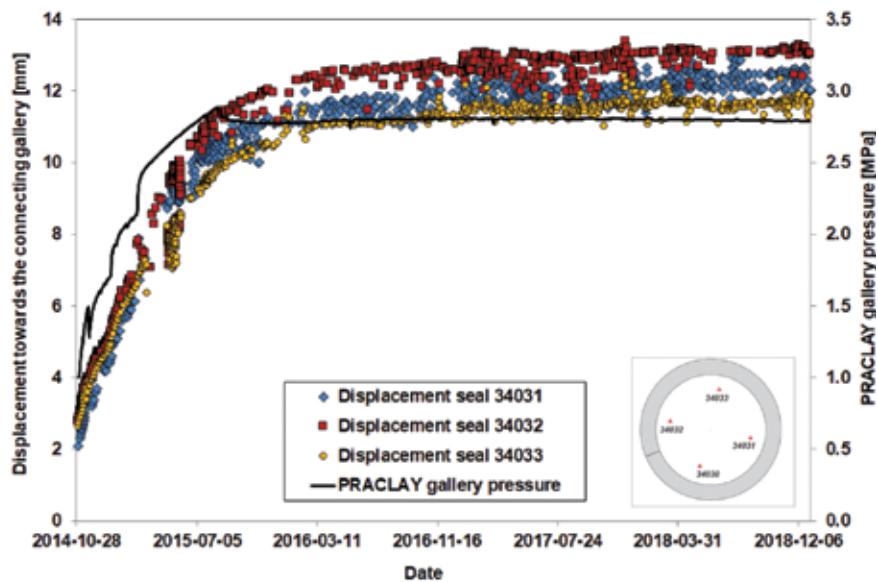
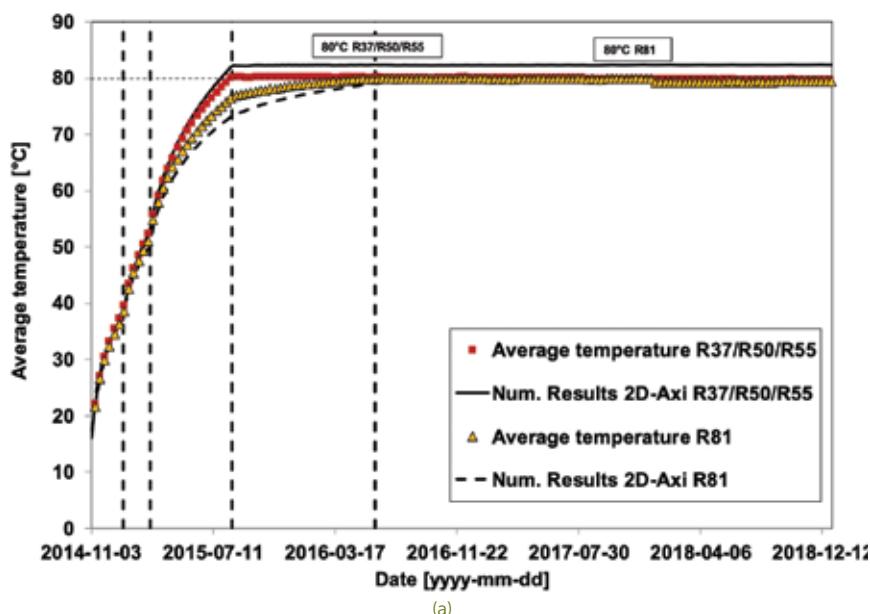


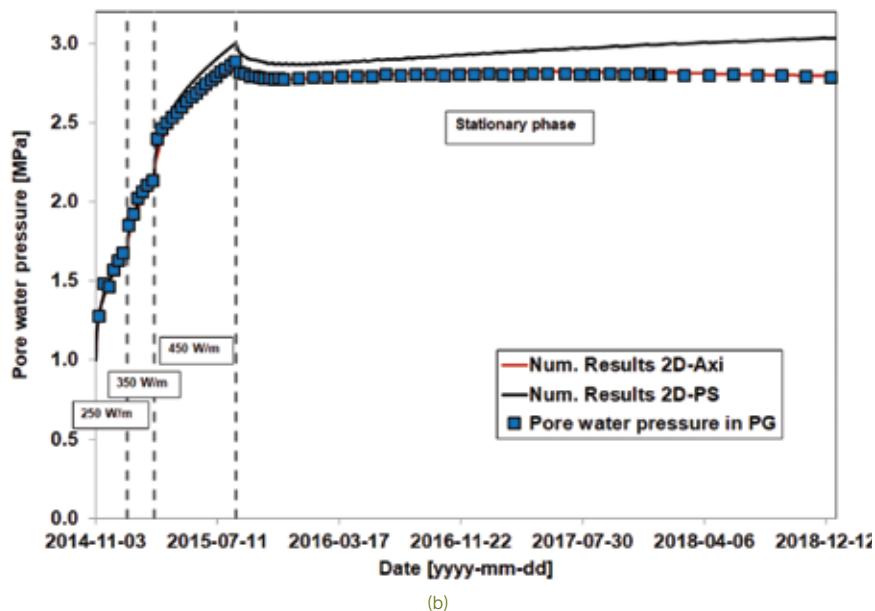
Figure 20 – Evolution of the movement of the seal structure towards the Connecting gallery since the beginning of the heating phase

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 numerical predictions, and to detect any deviations in the experimental results from these predictions. Figure 21 shows the evolution of the temperature at the interface between the lining and the Boom Clay and pore water pressure in the backfilled part of the PRACTAY gallery compared with the modelling results. Good agreement can be observed for both parameters. The pore water pressure modelled with the 2D plane strain model deviated from the measurements, which was inherent in this kind of model where the transverse dissipation of the pore water pressure was not allowed (Figure 21 b).



(a)



(b)

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

EVOLUTION OF THE PERMEABILITY OF THE BOOM CLAY AROUND THE CONNECTING GALLERY AND PRACLAY GALLERY

In order to study the excavation-induced permeability variation and subsequent self-sealing process, and to check the effect of heating on the permeability and self-sealing behaviour of the Boom Clay, systematic permeability tests were conducted in HADES.

In 2018 six additional permeability tests were performed on the PRACLAY gallery borehole filters located in the zone affected by a significant temperature increase, and the test results were compared with those obtained at these same filters before the PRACLAY Heater test. The comparison indicates that there is no significant thermal impact on the Boom Clay intrinsic permeability, which further confirms the observations from laboratory tests and the small-scale in-situ ATLAS heating test performed in HADES.

In order to analyse the thermal impact on the geochemistry of the Boom Clay, a large number of water samples were taken in 2018 from the geochemical filters where a significant temperature increase is observed. Based on the water sampling data, the permeability of the surrounding Boom Clay was derived. It is worth noting that these geochemical filters are ten times longer than the normal filters, so the derived intrinsic permeability is representative of a much larger volume of the Boom Clay. The derived values for the intrinsic permeability are found to be very close to those obtained from the neighbouring normal filters. This validates the permeability test results from the normal filters installed in the Boom Clay and confirms once again that the thermal impact on the Boom Clay intrinsic permeability is insignificant.

A report entitled "In-situ hydraulic conductivity measurement for the Boom Clay around the CG and PG" was prepared in 2018. The report contains a summary of all the in-situ permeability test results for the Boom Clay around the Connecting gallery and the PRACLAY gallery obtained between 2010 and 2018.

1.2.4 IMPROVED INTERPRETATION OF THE TEST RESULTS BY MODELLING

Continuous efforts were made in 2018 to improve the interpretation of the PRACLAY Heater test, which enables us to improve and confirm the THM characterisation of the Boom Clay.

IMPROVED INTERPRETATION OF THE MEASURED TEMPERATURE

The measured temperature from the PRACTAY Heater test was interpreted first, because the temperature variation in the Boom Clay is dominated by heat conduction and because the hydro-mechanical coupling effect on heat transfer can be ignored. This means that the interpretation is simpler than that of the measured pore pressure.

The small-scale ATLAS IV heating test was carried out before the start-up of the large-scale PRACTAY Heater test, and the interpretation of the PRACTAY Heater test was always cross-checked against that of the ATLAS IV heating test. For these two in-situ tests, the interpretation work was carried out using three-dimensional, purely thermal modelling and the analytical solutions. In 2018 all the sensor coordinates in both in-situ tests were double-checked. This provided more accurate information for the improvement of the numerical interpretation, resulting in an improved set of anisotropic thermal conductivities for the Boom Clay.

Most of the work described above was carried out before 2018. A report entitled "Three-dimensional thermal modelling of the PRACTAY Heater test", which summarises all the interpretation work, was prepared in 2018.

IMPROVED INTERPRETATION OF THE MEASURED PORE PRESSURE

The numerical prediction for the PRACTAY Heater test was made using a 2D-Axis THM model before switching on the heater. Up until now the predicted pore water pressure in the Boom Clay has shown reasonable agreement with the readings measured, which forms a solid basis for improved interpretation of the measured pore water pressure.

The improved interpretation proceeded stepwise. First the improved anisotropic thermal conductivity values derived from the previous three-dimensional thermal modelling of the two in-situ tests were used in the interpretation of the measured pore water pressure from the ATLAS IV heating test by means of 3D THM modelling. An extensive sensitivity analysis for the ATLAS IV heating test was then performed, indicating the high sensitivity of the Young's modulus on the small variation in the strain. Consequently, a modified Drucker-Prager model was proposed, and a new set of hydro-mechanical parameter values was obtained. Using these values, it was observed that all the measured pore water pressures in the ATLAS IV heating test are very well reproduced by the 3D THM modelling (see Figure 22).

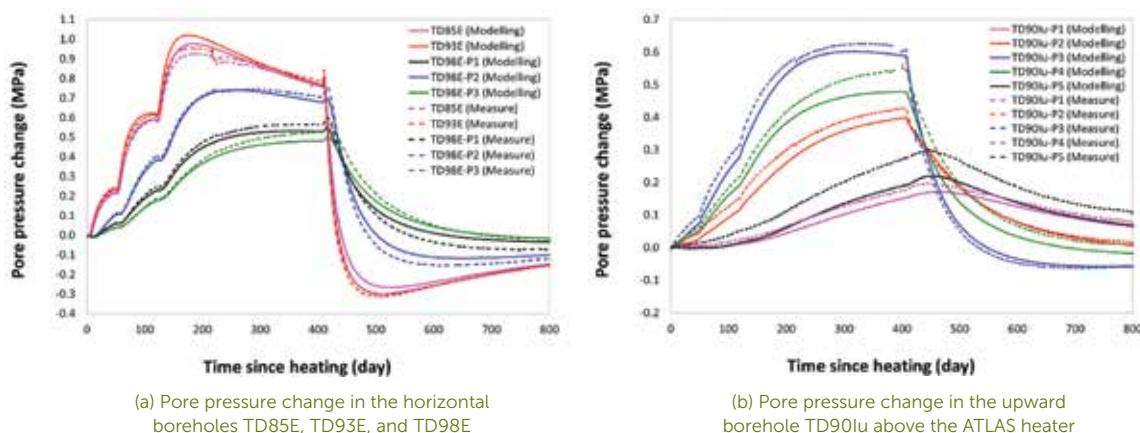


Figure 22 - Comparison of pore pressure change between modelling and measurement for ATLAS IV heating test

The proposed mechanical model and the new set of parameter values for the Boom Clay were validated by numerically reproducing the laboratory test results. The improved mechanical model and parameters for the Boom Clay were then used to improve the interpretation of the PRACTAY Heater test by means of 2D-Axis THM modelling. The modelling results were extensively compared with the measurements during the first four years of heating. Figure 23 presents the improved pore water pressure interpretation compared with the numerical prediction in the Boom Clay in the mid-plane of the PRACTAY Heater test. This shows that the improved mechanical model (modified Drucker-Prager model) enables a more regular distribution of the pore water pressure from the near field to the far field.

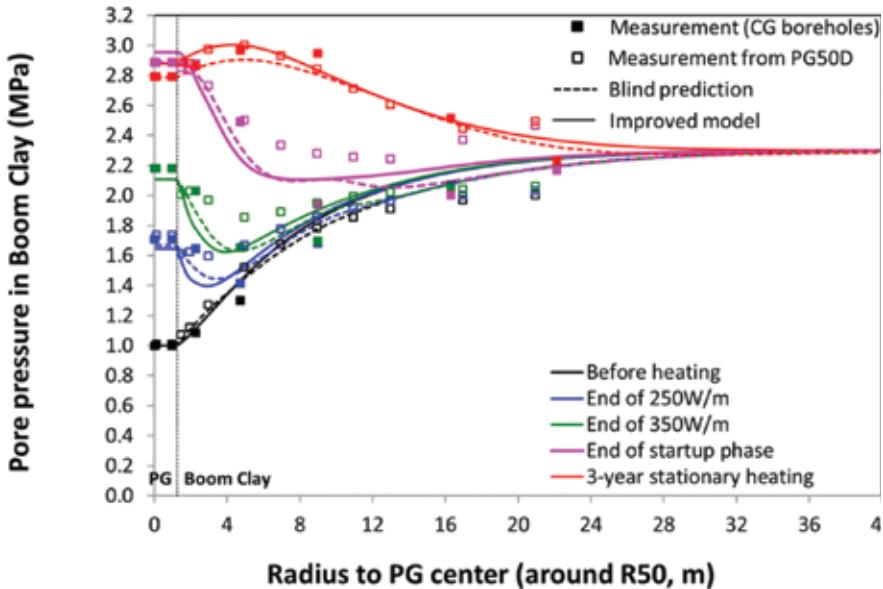


Figure 23 - Radial profiles of the pore water pressure around Ring 50

Nevertheless, Figure 23 still shows a small difference between the measurements and the modelling results. In this respect, it is important to know that the THM anisotropy of the Boom Clay and the drainage of the pore water into the Connecting gallery cannot be taken into account in the 2D-Axis THM model. Moreover, the possible variation in thermal conductivity, caused by excavation, and the layering of the Boom Clay formation above and below the PRACLAY gallery were not considered in the actual modelling. These factors probably contribute to the deviation between the modelling and the measurement, and could be taken into account in future interpretations.

All the work described above has been brought together in a draft report entitled "Two-dimensional coupled THM modelling of the PRACLAY Heater test: an interpretation after three years of stationary heating" (under review).

1.2.5. INSTALLATION OF NEW BOREHOLE CG62E

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, both numerical modelling and in-situ observations indicated that the thermally and hydro-mechanically affected zone as a result of the PRACLAY Heater test would extend further than the existing instrumented boreholes. It was decided to extend the monitored temperature and pore water pressure field from the PRACLAY Heater test with the installation of a new horizontal borehole CG62E at a distance of 29 m from the PRACLAY gallery (Figure 24).

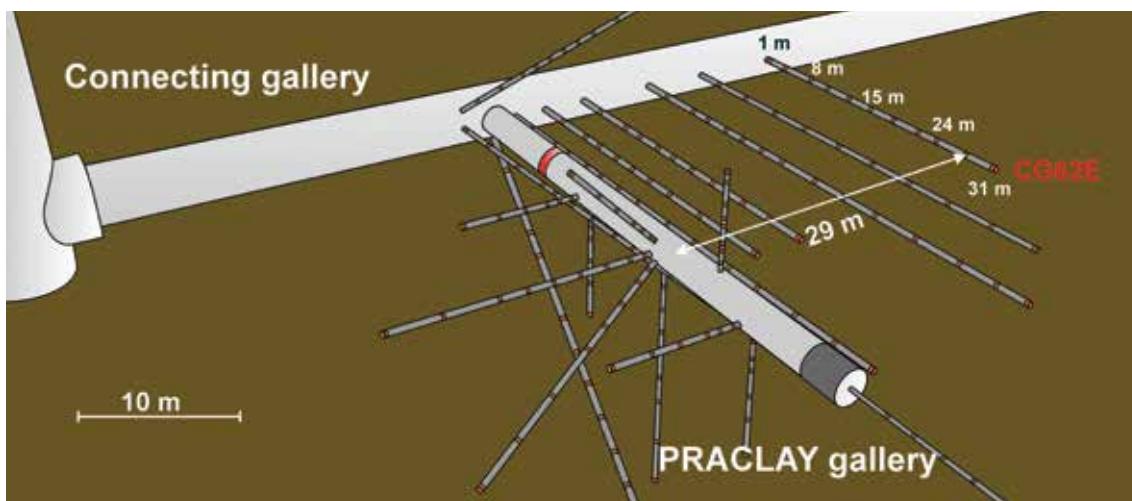


Figure 24 - Location of the new borehole CG62E

In January 2018 this borehole was successfully drilled from the Connecting gallery and instrumented with thermocouples, pore water pressure sensors and total pressure sensors. Figure 25 shows the pressure build-up in the 11 filters of this instrumented borehole since then. At the end of 2018, the measured pressure values almost reached the steady state values in non-heated conditions. The thermally affected zone has not yet reached this part of the host rock, as the temperature sensors along this borehole do not indicate any response to the heating of the PRACLAY gallery.

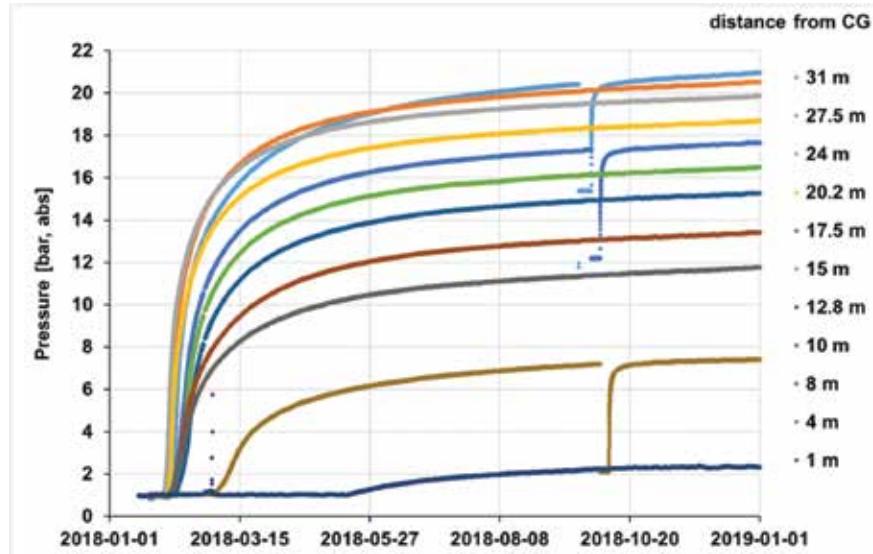


Figure 25 – Evolution of the pore water pressure in the instrumented borehole CG62E

1.2.6. PRELIMINARY ASSESSMENT OF THE PRACLAY HEATER TEST OBJECTIVES

An initial preliminary assessment of the Heater test objectives was made in 2017. Additional information gained in 2018 confirmed the conclusions drawn from the 2017 assessment and indicate that the whole experimental set-up is working as expected, indicating early success in this experiment after more than four years of heating:

1. The heating system continues to deliver the correct amount of power needed to run the experiment with the 80°C boundary condition.
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 (e.g. total pressure sensors in the concrete lining blocks) 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 (see Section 3 Instrumentation & Monitoring).
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 four 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 more than four 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 improved interpretation of both the PRACLAY Heater test and the small-scale ATLAS IV heating test confirms that the heat transfer mechanism is by conduction. This has enabled us to refine our knowledge of the characteristics of this mechanism.
 - 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. Confirming this structural integrity under thermal stresses is one of the main objectives of the PRACTCLAY Heater test.

- 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.

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 synthesis report on these studies was written and delivered in 2018. The main conclusion is that the state of stress inside the gallery was higher than expected (designed), but was still significantly lower than the ultimate strength of the concrete. The report also indicated that further analysis was 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. This interaction is a critical aspect in correctly designing the access and repository galleries of a geological disposal facility. The next step in the study will be to set up a new programme to address the questions arising from this report. This will be done in the course of 2019 in direct collaboration with ONDRAF/NIRAS.

2.2. Micro-seismic monitoring programme

The micro-seismic system around the PRACTCLAY gallery was installed in two phases between September 2006 and January 2008 and consists of 23 transmitters and 19 receivers (Figure 26 & Figure 27). The system has been operating continuously since 2006.

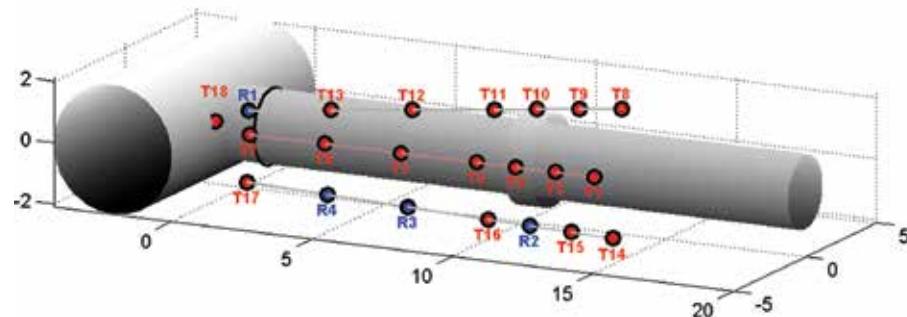


Figure 26 - [Red] transmitters (T) and [blue] receivers (R) installed in September 2006

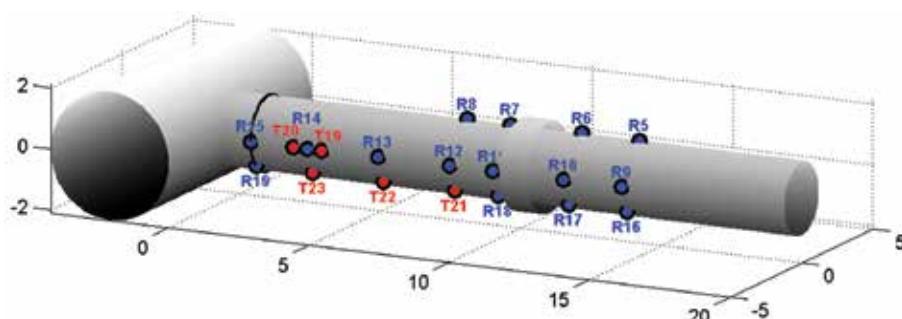


Figure 27 - [Red] transmitters (T) and [blue] receivers (R) installed in January 2008

The original objective of these micro-seismic measurements was to monitor the evolution of the host rock quality by measuring seismic velocity and damping over time, thereby assessing the influence of the different PRACLAY phases: from gallery excavation to heating. An overall assessment of the quality of the data was made after selecting relevant transmitter-receiver pairs. This assessment included a preliminary analysis of the waveforms and an estimation of some resulting geomechanical parameters of the surrounding host clay formation, based on the interpretation of the compressive (P) and shear (S) wave velocity.

Since the effect of the different phases, and in particular the heating phase, was not always unambiguously clear, we decided to opt for an independent analysis by the company that installed the set-up (GMuG). As agreed with GMuG, this analysis will be performed in two phases. The first phase deals with the selection of data sets and the interpretation methodology. The actual interpretation and analysis would then take place in the second phase. The order was placed in September 2018, with the actual work scheduled to start early in 2019.

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.

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 is co-funded by ONDRAF/NIRAS and SCK•CEN's Academy and is a joint collaboration with Laboratoire Navier/CERMES, l'École des Ponts ParisTech. This project was awarded to Awarken MAY, who started working on it in October 2018.

2.3.1. MULTISCALE APPROACH TO MODEL EARLY AGE THERMO-HYDRO-MECHANICAL BEHAVIOUR OF NON-REINFORCED CONCRETE

This PhD research topic has direct relevance to concrete engineered barriers, which are an integral part of nuclear waste disposal concepts developed in Belgium.

Two years of PhD work have just been completed. Year 2 focused on comprehensively establishing the validity of a pore network model in predicting water sorption isotherms, which is a key input datum for predicting drying shrinkage strains, given that a poro-elastic framework was adopted. Significant improvements were made to the source code for a pore network model to handle the hierarchical pore structure of cement paste. The model was validated with 11 sets of experimental data with very good agreement and no calibration parameters. A paper is currently in preparation for submission to an appropriate journal in 2019.

The following milestones were achieved in 2018: (i) a paper was published during the CONMOD 2018 (Delft) conference concerning drying shrinkage, (ii) a guest lecture was delivered on the Topical Day (Cementitious materials in nuclear applications: a glimpse on coupled degradation processes affecting long-term durability) held at SCK•CEN on 18 September, (iii) a presentation on the prediction of drying shrinkage strains was presented on the PhD Day held at SCK•CEN on 19 September, and (iv) a poster was published in the IGD-TP Exchange Forum 8 on 3 and 4 December (<https://igdtp.eu/event/igd-tp-exchange-forum-8/>).

Currently, work is continuing on revisiting drying shrinkage theory, with a view to understanding the reason for the typical underestimation of drying shrinkage strains with existing models.

2.3.2. INVESTIGATION OF THE LONG-TERM HYDRO-MECHANICAL BEHAVIOUR OF THE BOOM CLAY

The long-term creep behaviour of the Boom Clay has been addressed in many studies, in terms of experimentation, constitutive modelling and numerical analysis (CERMES 2009, IRSM 2010, 2015, 2017). Based on these studies, a body of evidence of creep behaviour has been established. Nevertheless, it appears that there are still certain issues that need to be further investigated, closely linked with problems such as gallery convergence during construction and long-term interface behaviour between the Boom Clay and the galleries. These phenomena are very important, especially during the operational phase where the repository galleries are open for a few decades before emplacement of the supercontainers and backfilling of the gallery. The main objective of this PhD thesis is therefore to improve our understanding of the long-term behaviour of the Boom Clay with a new experimental programme that includes both laboratory and in-situ tests in the HADES URL in order to further develop a relevant constitutive law and implement it in a finite-element code. The PhD started in October 2018 and the first year will be devoted to a literature review with a view to setting up and starting a new experimental programme.

2.4. Core Management & GSIS

EIG EURIDICE coordinates the management of the ONDRAF/NIRAS drill cores. This includes packaging cores to ensure good conservation 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. The packaged drill cores are stored in the core library (Figure 28).



Figure 28 – Storage of packaged drill cores at EIG EURIDICE

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, experimental set-ups, samples, analyses, etc. in the context of the Belgian radioactive waste disposal programme, and ensures the traceability of validated geoscientific data.

Work in 2018 focused on two major topics:

- GSIS support for core management,
- Improvement of the GSIS user interface.

Support for core management included the development of a complete workflow to track all information about a specific core, from core request to every operation that was applied to a core during the sampling process. For this, object-tracking metadata records (Figure 29) are made for each core. These metadata can be used for the pre-selection of samples requested for research. The metadata records can be completed with links to the scientific outcome of research on these cores. The core management workflow in GSIS was successfully tested in 2018 during the sampling campaign for a selected core request.

The screenshot shows a software interface titled "Request 2018-004". The main area is divided into sections: "Details", "Tracking", and "Tracking attachments".

- Details:** Shows the request ID (2018-004), creation date (2018-05-18), end date (not specified), status (Research results available), research topic (Trial treatment of organic matter from Room City formation), institution (Srophos21 Consultants), contact person (Hermes Beurak-Rimkus), request ID (2018-004), request link (https://www.beurak.be/page/), and results link (Vignette) (https://www.beurak.be/page/).
- Tracking:** A table with columns: Name, file description, Date, and Link. One entry is visible: "Core request 2018-004" (pdf of the core request, 2018-05-18, https://www.beurak.be/page/).
- Tracking attachments:** A section showing a single attachment named "Core request 2018-004" (pdf, 2018-05-18, https://www.beurak.be/page/).
- Related objects found:** A section indicating "23 related objects found".
- Buttons:** "Download to Excel" and "Cores (23)".

Figure 29 – Illustration of the object-tracking metadata record, representing a core request

To finalise the core management support in GSIS, further development efforts are needed to generate a summary file on cores and boreholes directly from GSIS. Furthermore, GSIS needs to be completed with all data that are still stored in Excel files.

Other development efforts in 2018 focused on improvements to the GSIS user interface. These changes are due to be implemented in spring 2019 and will enable more straightforward use of GSIS, with more transparency and improved accessibility of data.

3. Instrumentation & Monitoring

Most of the work in 2018 on instrumentation and monitoring was devoted to assessing the sensor performance of experimental set-ups.

Sensor performance assessment

Since construction work on HADES began in the early 1980s, many experimental set-ups of different sizes and for various purposes have been implemented in the various galleries of HADES. Some of the sensors installed are still accessible, sometimes even functional, and closer investigation of the instrumentation can therefore give us very valuable insight into the long-term performance of sensors, and which factors determine a successful monitoring operation in the long term. This knowledge will be very relevant for the monitoring design of future large-scale experimental set-ups and optionally for a radioactive waste repository. ONDRAF/NIRAS therefore decided to launch a research programme to systematically assess the performance of these HADES URL monitoring set-ups.

The first study, initiated in 2015, dealt with the performance assessment of the instrumentation installed as part of the CLIPEX project. The final version of the CLIPEX sensor performance study was published in May 2018.

Meanwhile, the second study was started, which looked at the PRACTYL in-situ experimental set-up. It followed the same methodology as that developed for the CLIPEX experimental set-up: by assessing the measurement performance of each individual sensor, the success factors for a monitoring set-up (sensor technology used, installation, sensor environment, accuracy and representativeness) can be derived.

After detailing the assessment methodology and the scope, the historical context was outlined. This covered a 16-year time span, from installation of the first multi-filter piezometers in 2002 up to the most recent instrumented borehole in 2018. The next part was devoted to a detailed description of the monitoring set-up. The 1200+ sensors were grouped into 32 "sensor sets", each containing similar sensors (same technology) that were installed in similar conditions.

The assessment is made by checking each individual sensor against a number of criteria. The five main categories of criteria that were defined for the first study have been applied again. These categories are installation, operation of the sensor, environment, signal quality and sensor characteristics. The

criteria in the “installation” category contain, for example, the date of installation or the availability of formal installation procedures. The “environment” category specifies the host medium of the sensor, the temperature to which the sensor is exposed, etc. The “sensor characteristics” category includes calibration parameters (making it possible to derive long-term drift) for the accessible sensors (more specifically pressure transmitters).

The assessments are summarised in spreadsheet tables (one for each sensor set). The contextual information and the conclusions are recorded in the corresponding assessment section of the report. By the end of 2018, relevant progress had been made on this assessment section. The first few months of 2019 will be devoted to finishing the report, conducting an internal review and holding discussions with ONDRAF/NIRAS.



Non-accessible sensors

This study was set up to address the issue of how to assess the sensor output when the sensor itself is no longer accessible. This is the case with many, if not most, sensors in field set-ups in HADES, and will therefore also be applicable for repository monitoring. Calibration, although highly recommended due to the long monitoring periods, is not possible in these conditions. Consequently, to validate the readings of non-accessible sensors, alternative diagnostic tools to assess the sensor functionality needed to be developed.

Two particular sensor technologies that are among the most popular used by EURIDICE are vibrating wire sensors and thermocouple sensors. Vibrating wire sensors were already investigated in detail in the CLIPERX assessment study, so the experimental part of this study focused on the thermocouple sensors. A field calibration technique, which had been developed earlier in this study (2016-2017), was tested in the surface lab, as well as in-situ, on both functional and artificially damaged thermocouple sensors. The field calibration technique consists in modifying the temperature of the accessible end of the thermocouple (“cold junction”); because of the symmetric properties of a thermocouple, this also results in a changing output signal, which could indicate the validity of the thermocouple signal.

Upon completion of the study, we concluded that changing the temperature at the cold junction and measuring the resulting output allows performing a zero check or measurement, and to check the sensitivity (and compare it with the expected value). The technique developed however cannot ~~a~~ a real thermocouple calibration, as the condition of the upstream part (towards the measuring end) is not well characterised by this test procedure. On the other hand, it can give a decisive answer on the question if the thermocouple reading is reliable, and provide additional confirmation of the measurement characteristics (in particular sensitivity) of an unsuspected thermocouple in the long term. When a thermocouple starts displaying unexpected behaviour, other – more straightforward – techniques, such as impedance measurement (continuity and isolation), are a more efficient way to check the functionality of the sensor. These latter techniques cannot also be included in a follow-up measurement programme for all relevant thermocouples in HADES.

4. Participation in international research projects

4.1. European Commission (EC) projects

Modern2020

As part of the Horizon 2020 Euratom Work Programme NFRP6-2014 “Supporting the implementation of the first-of-the-kind geological repositories”, a project called “Modern2020” was approved by the EC in early 2015. The objectives are to investigate monitoring strategies, technologies, demonstrations and stakeholder interaction in the context of geological radioactive waste repositories. The project started on 1 June 2015 and will run for 48 months (until 31 May 2019). 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 2018 EURIDICE completed its contributions, which dealt with 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 EIG EURIDICE subcontractor in this project, which has developed a miniature interrogator (optical spectrum analyser) for these FBG sensors. In addition, the irradiation programme for the optical sensors at SCK•CEN was finalised early in 2018. The results were reported to the task leaders.

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. In early October 2018 EURIDICE organised a three-day workshop at Saint-Dizier and the Centre de Meuse/Haute-Marne in Bure (F), during which the final structure, main objectives and content of the final WP4 deliverables were discussed.

EIG EURIDICE also participated in the General Assembly in June 2018 in Sargans (CH). Although we are not formally contributing to WP5, we also attended the conference with the citizen stakeholders, organised by the University of Antwerp in September 2018, as technical experts.

Furthermore, further preparations have been made for the Modern2020 International Conference (April 2019 in Paris) and the Monitoring School (May 2019 in Oskarshamn and Äspö, Sweden).

European Joint Programme on Radioactive Waste Management and Disposal

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

In 2018, EURIDICE contributed further to the development of these two RD&D work packages in close cooperation with the work package leaders and other partners to clearly define the RD&D activities of EURIDICE.



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 2018 included: characterisation of reference materials for food safety and nuclear decommissioning, and 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 CO₂, and support to international research groups performing studies. A new field of research concerns natural archives. In 2018 samples were analysed from Greenland ice cores and corals from both tropical waters and cold water. The latter projects were carried out within JRC-Geel's external access programme and aim at improving our understanding of past natural and anthropogenic events. Radioactivity measurements can provide a timescale for past events. One particular highlight was the Japanese award given for a paper published in the Journal of Oceanography, in which oceanographers describe new findings on ocean currents based on data from the HADES URL. Such information is vital to make better models of the world's climate in order to predict the effects of climate change.

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.

4.2. Other international collaborations

A "Compendium of RD&D results carried out at Underground Research Facilities (URFs) for Geological Disposal" will be published as one of the IAEA's Nuclear Energy Series documents on research activities carried out at underground research facilities over 50 years. This document is intended to support IAEA Member States that would like to initiate and develop their geological disposal programmes, by

providing a reference where they can find more in-depth information and reports on URF RD&D results. The objective of this document is to provide an overview of the existing URFs around world, and a comprehensive overview of the main information on RD&D results obtained from URFs to date, presented with an understanding of how this contributes to the scientific and technical basis for the feasibility and safety of geological disposal, in a range of host rocks.

In April 2018 EIG EURIDICE was invited by the IAEA to attend a "Consultancy Meeting on the Compendium of RD&D Results carried out at Underground Research Facilities (URFs) for Geological Disposal". The IAEA organised a Technical Meeting on the Compendium with representatives of nearly all Member States at the beginning of September 2018, attended by EURIDICE's scientific manager, Xiangling Li, as the Belgian representative. Several Member States were invited to make a presentation on their national programme. A presentation on "The roles of the URL HADES in the Belgian RD&D program on radwaste geological disposal" was given by Xiangling Li.

~~On 24–26 August China organised "The 7th China Symposium on Underground Waste Disposal & International Workshop on Radioactive Waste Disposal", during which an international session on "THMC Coupling Process and Gas Transport in Geological and Engineered Barriers" was jointly organised by Lille University, ANDRA, BRIUG of CNNC, Hohai University and Tongji University. In the international session, Xiangling Li, as an invited speaker, delivered a presentation entitled "Multi-scale investigation of the Boom Clay THM behaviour at Belgian URL HADES (in the context of geological disposal of HLW)".~~

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 radioactive waste in clay.

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 as the reference option for the management of category B waste (low- and intermediate-level long-lived waste – LILW-LL) and C waste (high-level waste – HLW and spent fuel). Within this framework, the reference scenario considered by ONDRAF/NIRAS for research, development and cost assessment is geological disposal, in a single facility, on Belgian territory, in poorly indurated clays. This scenario involves 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 400 m and 600 m, respectively (Figure 30).

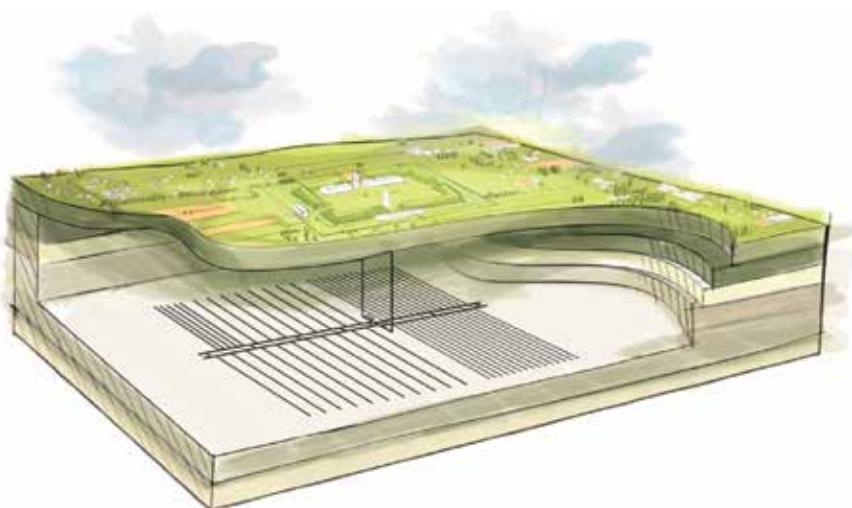


Figure 30 – ONDRAF/NIRAS's conceptual design of the geological disposal facility

Within this context and at the request of ONDRAF/NIRAS, EURIDICE developed a numerical model to simulate the thermal response of the geological disposal facility when heat-emitting C waste (future vitrified waste (CSD-V) – i.e. vitrified waste to be produced in the future if reprocessing of spent fuel elements resumes – or spent nuclear fuel assemblies (UOX - 8ft, UOX - 12ft, UOX - 14ft and MOX)) is placed in the disposal galleries. The numerical model was developed using the finite-element software COMSOL multiphysics® and was able to calculate the temperature evolution in both the engineered and the natural barrier system (i.e. the Boom Clay and the Ypresian clays), respectively.

The ultimate objectives of the research were:

- To identify the most significant parameters for the temperature evolution in the engineered barrier system and in the natural barrier system;
- To evaluate the temperature field inside the geological disposal facility (i.e. inside the engineered and the natural barrier system) 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 31;
- The cementitious backfill filling the gap between the supercontainer and the concrete segmental lining of the disposal galleries;
- The concrete segmental lining of the disposal galleries.

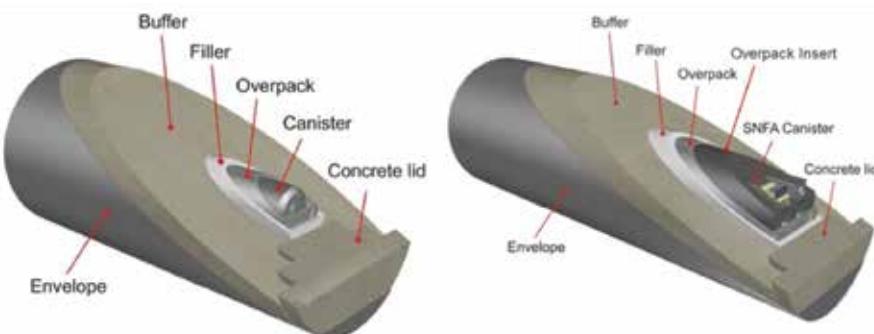


Figure 31 - Supercontainer for vitrified high-level waste (left) and UOX irradiated fuel (right)

The research considers both the Boom Clay and the Ypresian clays and evaluates the impact of the geological disposal facility depth on the temperatures in both the engineered and the natural barrier systems. Three depths were taken into account, i.e. 200 m, 400 m and 600 m. The 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).

The report concerning this analysis was delivered in June 2018. The numerical results confirmed and validated the geological disposal facility reference layout and in particular the distances between the disposal galleries, i.e.:

- 120 m between two consecutive disposal galleries with the spent nuclear fuel supercontainers (SC-2, SC-3, SC-4 and SC-5)
- 120 m between two consecutive disposal galleries with the CSD-V FUTURE (i.e. vitrified waste to be produced in the future if reprocessing of spent fuel elements resumes).

The research work confirmed that the geological disposal facility design enables good dissipation of the heat, which guarantees that the temperature evolution in the near field and in the far field stays in line with the temperature reference values in the engineered and the natural barrier system. The study also shows that the thermal properties of the concrete buffer are a critical parameter in the evolution of the temperature around the supercontainer. Further research will be performed to fully characterise and optimise this parameter.

The thermo-hydro-mechanical evolution of the clay was not taken into account in this research. A new study was therefore launched in late 2018 to assess the thermo-hydro-mechanical evolution of a geological disposal facility. This new study consisted in building a thermo-hydro-mechanical finite-element model in COMSOL, which took into account the reference layout and the reference schedule for the disposal of the supercontainers. As the far-field clay behaviour is the main concern in this work, the engineered barrier system components were not taken into account to simplify the analysis. The study started in September 2018 and the report with the results will be delivered in March 2019.

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

As manager and operator of the HADES URL, EIG EURIDICE 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. EURIDICE is in charge of the daily management, follow-up, scientific operation and reporting of the long-term, large-scale PRACTIC Heater test.

In addition, EIG EURIDICE supports ONDRAF/NIRAS by writing topical documents on specific aspects of the geomechanical behaviour of the Boom Clay. Scientific publications and reports, such as 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 or the scientific interpretation of the long-term, large-scale PRACTIC Heater test, constitute significant inputs to the Safety and Feasibility Case of ONDRAF/NIRAS, planned for 2022.

RD&D Part 2

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. Subsequently, FANC analysed the safety report and its supporting documents and asked about 300 questions. The answers to these questions were approved by FANC by the end of 2017. In the course of 2018 ONDRAF/NIRAS and its partners incorporated the answers to the questions from FANC into an update of the safety report and supporting documents. The revised safety report and supporting documents will be submitted to FANC in January 2019.

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.

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

As a result of FANC's questions, a new iteration of the radiological long-term safety assessments was performed in the period 2014-2018. In 2018 the results of this new iteration were reported and verified in detail.

Hydrogeological models

Point dilution tests on a seasonal basis were continued in order to carry out at least eight tests per piezometer (Figure 32). The test results obtained will be interpreted during the first half of 2019, after finalising the updated version of the safety report. This should enable the groundwater fluxes during dry (summer) and wet (winter) conditions to be reliably evaluated. The groundwater levels were measured on a monthly basis: this information is needed to determine the gradient of the water table in the vicinity of the disposal site.



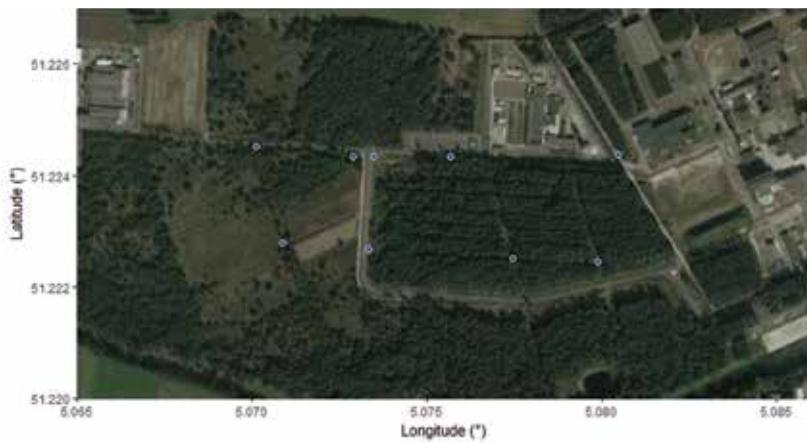


Figure 32 - Location of the nine piezometers used for point dilution tests, part of the additional experimental programme for validation of the hydrogeological models

Two large-scale pumping tests were organised towards the end of 2018 in order to confirm the hydraulic permeability of the upper aquifer. This aquifer is locally (at and around the disposal site) characterised by a coarser facies of the Upper Mol sands. As the former pumping tests (ON-Dessel-2, ON-Dessel-3 and ON-Retie-1) focused on the hydraulic behaviour of the Kasterlee Clay, which separates the lower from the upper aquifer, no appropriate high-quality data was available for the latter. A total of eight new piezometers were installed for this purpose (Figure 33 and Figure 34). Pumping tests were performed with discharges between 10 m³ and 35.5 m³ for at least one and a half days (pumping phase) on two different levels (Upper Mol and Lower Mol). The tests will be interpreted in early 2019.



Figure 33 – Location of large-scale pumping tests. Eight new piezometers were installed for this purpose. Both clusters are composed of two pumping wells, 15 m and 30 m deep, equipped with a piezometer 250 mm in diameter to allow the installation of a pump. Additionally, each cluster also has two observation wells, each equipped with a double piezometer. Other nearby piezometers were also monitored during the tests. Arrows indicate the direction of the pictures shown in Figure 32.



Figure 34 – Upper picture: three of the four piezometers in the “West” cluster; L-110 and L-111 are the pumping wells and L-113 and L-112 (not shown) are the observation wells. Lower picture: “East” cluster with pumping wells L-106 and L-107 and observations wells L-108 and L-109.

Test cover

As construction of the test cover has been postponed, and work had to focus on finalising the safety report and its supporting documents, nothing or very little was done on this project. Work will resume in 2019.

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 33).

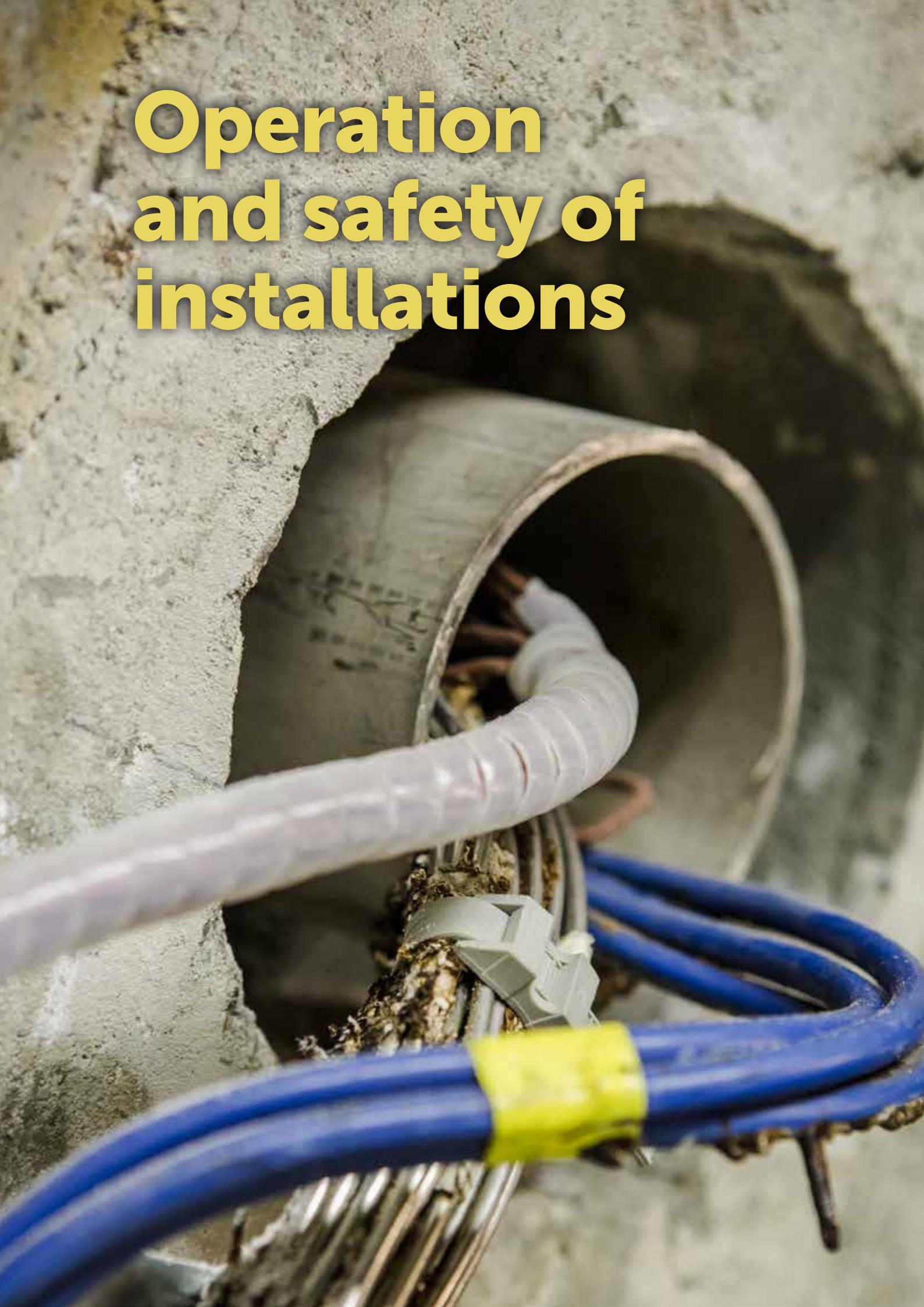


Figure 35 - Overview of the demonstration test

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 2018. Some data collection and analysis continued, however.

Operation and 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 2018 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 the action points from the JAP (JaarActiePlan): prevention policy, fire safety, the electrical installations, hazardous products and shaft 1 refurbishment.

The operations team gave technical support to RD&D activities for different projects and to communication activities:

- Connection of monitoring devices to the data-logging system in HADES;
- Technical support to the PRACLAY Seal and Heater experiment;
- A borehole drilling for the installation of a new piezometer for the PRACLAY Heater experiment;
- Installation of a new seismometer set-up both underground and in shaft 2;
- Sampling campaigns on core samples;
- Operation of the hoisting system and technical assistance during visits.

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 ONDRAF/NIRAS financing agreement covering the period 2016-2020, a budget for the refurbishment of the shaft 1 hoisting system has been put in place. After project preparations in 2016 and the appointment of an engineering company in 2017, the project work in 2018 focused on finalising the shaft stability study and on identifying the regulatory requirements, in interaction with the safety authorities. Both topics were successfully addressed in 2018. The specifications for the design and build phase were defined and the public tendering procedures were launched for the three lots: (1) hoisting machine building; (2) technical installations (electricity, heating, ventilation, air conditioning and pump) and (3) the hoisting system. Bids for the different lots are expected at the beginning of 2019, with final tendering decisions by mid-2019. The necessary action was taken to initiate the procedure for a building and environmental permit for the works. The permit application is due to be submitted in early 2019 with a view to obtaining the permit before mid-2019.

A new system for communication between underground infrastructures and above-ground installations was installed at the end of 2018. The system is set up in a redundant way by means of two repeaters at each shaft. Above-ground communication is covered by antennas, while the underground infrastructure (shafts and laboratory) is equipped with leaky feeder cables. Communication is via walkie-talkies. Provisional acceptance of the system is expected at the beginning of 2019.

In collaboration with the Royal Observatory of Belgium, a new seismometer set-up has been installed underground. This set-up includes four seismometers in the underground lab (Connecting gallery, PRACLAY gallery and Test Drift), and one in shaft 2.

In collaboration with JRC-Geel, a new oxygen measurement system has been installed. This will be used to monitor oxygen levels in the part of the underground lab used by JRC-Geel.

Above-ground installations and buildings

The operations team carried out standard maintenance and necessary repairs on the installations, buildings and infrastructure in 2018. Work on removing the ESDRED experiment was completed. The concrete floor was poured and the green hangar was rebuilt.

EIG EURIDICE signed up for the Green Deal "Bedrijven en biodiversiteit" (companies and biodiversity). The aim of this deal between companies and the Flemish government is to create more biodiversity on company sites. It is mainly based on the idea of creating more natural habitats for both fauna and flora, natural habitats that are less high-maintenance, etc. A public tendering procedure was launched for the preparation of a management plan on biodiversity. This study had been granted to Biotoop by the end of 2018 and will start in early 2019.

Licences

The **operating licence** is valid until 2024. Due to important changes to the infrastructure (shaft 1 renovation project), a new operating licence will be necessary. Meetings have been set up with the Federal Public Service for Employment, Labour and Social Dialogue and the community of Mol to start preparing the application for a new permit. This work will continue in 2019.

The **nuclear licence** of EIG EURIDICE (issued in July 2017) is valid until 2021. In May 2018 FANC granted an amendment to this licence to include the radioactive sources used by JRC-Geel in the HADES URL under the EIG EURIDICE nuclear licence. 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. As a new building and environmental permit needs to be requested for the shaft 1 renovation project, a revision for the environmental licence was prepared. The content of the existing licence was updated to reflect the current situation and the requirements for the shaft 1 renovation project were included. The application for the revised licence is expected to be submitted at the beginning of 2019.

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 38 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.

1. Visits

1.1. General

Anyone over the age of 18 can visit EIG EURIDICE and the underground research laboratory. Fifth- and sixth-year secondary school students can visit the permanent exhibition on geological disposal research. These school visits are usually combined with a tour of one of SCK•CEN's installations or a visit to ISOTOPOLIS, the information centre of ONDRAF/NIRAS and Belgoprocess in Dessel.



In 2018 EIG EURIDICE welcomed a total of 3,300 visitors in the course of 196 visits to the HADES URL and the above-ground exhibition on geological disposal (Figure 36). This is 842 more than in 2017 and represents the best year ever.

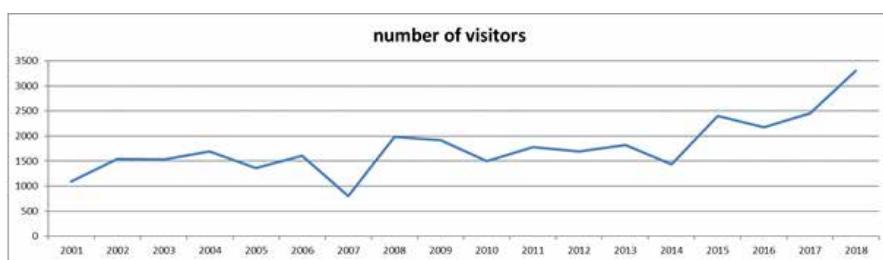


Figure 36 - Number of people visiting EIG EURIDICE since 2001

Figure 37 gives an overview of the different types of visits. Of the 196 visits in 2018, 45 involved sociocultural organisations. These "standard" visits take about two hours (1 hour exhibition, 1 hour tour of HADES URL) and are led by trained guides, who are also in charge of visits at ISOTOPOLIS. Sixty-three of the 196 visits involved direct stakeholders of EIG EURIDICE or were arranged at the request of SCK•CEN or ONDRAF/NIRAS. These are designated as VIP or technical visits and include geological disposal experts, journalists, and key political and economic figures. They are given a personalised guided tour by scientific staff, the Communication Manager and/or the Director of EIG EURIDICE, sometimes accompanied by ONDRAF/NIRAS or SCK•CEN management.

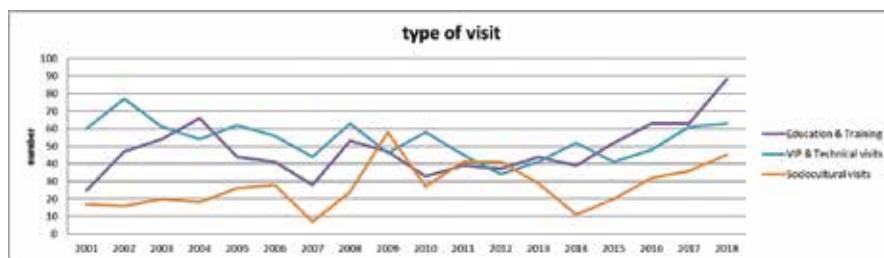


Figure 37 - Trends in the different types of visits

The majority of the visits (88) were for training and educational purposes, ranging from secondary school students to university students with a scientific background and adult training courses for people working in the field of nuclear applications. They represent the fastest-growing group of visitors. One of the reasons for this remarkable trend is promotional efforts directed at secondary schools to attract them to the permanent exhibition. As they are under the age of 18, they cannot go underground. In 2018, 30 secondary schools visited the surface installations and exhibition, representing 581 students.

In 2018 a new tool was developed to obtain more detailed feedback from visitors to the permanent exhibition and the HADES URL (Figure 38). This feedback tool will be used from 2019 on and will give us a better understanding of the impact of the visits we offer.

Last week, you visited the EURIDICE exhibition space and/or the HADES underground laboratory. Your opinion is important to us. We want to know what you thought of your visit and what we could improve in the future. That is why we are sending you this questionnaire. Participation is completely anonymous. It will only take five minutes of your time and it is not mandatory. We would greatly appreciate it if you would fill in this questionnaire so that we can improve our work.

EURIDICE GIE

Which parts did you visit?

Only the part above ground
 Both above and below ground

Figure 38 – Feedback tool for visitors

1.2. VIP visits

On March 21 2018, EIG EURIDICE had the honour to welcome Yukiya Amano, Director-General of the IAEA. Mr Amano was accompanied by SCK•CEN Director General Eric van Walle, SCK•CEN Chairman of the board Derrick Gosselin, and ONDRAF/NIRAS's long-term waste management director Philippe Lalieux. Peter De Preter, Director of EIG EURIDICE, showed Mr Amano around the HADES URL to apprise him of Belgian research into geological disposal in poorly indurated clay (Figure 39). The visit was part of a working visit to SCK•CEN with a special interest in BR2 (medical applications) and HADES.



Figure 39 – Visit by Yukiya Amano, Director-General of the IAEA to the HADES URL

EIG EURIDICE was also very pleased to welcome Zhang Jianhua, Vice Chairman of the China Atomic Energy Authority (CAEA) on 16 October 2018. He was accompanied by SCK•CEN Director General Eric Van Walle, EURIDICE RD&D responsible Xiangling Li and Team manager Mieke De Craen (Figure 40). The particular purpose of Mr Zhang's visit to Belgium was to sign a Memorandum of Understanding with Belgium's Federal Public Services for the Economy to strengthen collaboration on the peaceful use of nuclear technology. Mr Zhang's delegation was mainly composed of waste experts including the Vice President of China National Nuclear Corporation (CNNC) He Zixing and the Vice President of Beijing Research Institute of Uranium Geology Wang Ju. The goal of the mission was to prepare a decision to invest and build an underground research facility in Beishan, China for the purpose of studying geological disposal in granite.



Figure 40 – Visit by Zhang Jianhua, Vice Chairman of the China Atomic Energy Authority (CAEA), to the HADES URL

1.3. New approach for school visits - "DE BERGEMEESTERS"

Work started in 2018 on the design, testing and implementation of a new type of visit for secondary schools (Figure 41). Using a game format, students are divided into several teams to find a solution to the long-term management of high-level and long-lived waste. By taking on different roles in a community context, they discuss the needs, advantages and disadvantages of constructing a geological repository in a local community. The winning mayor becomes the so-called "Bergemeester"¹. Our aim with this game is to make the visits more dynamic and interesting for young people. By placing more emphasis on discussion and less on detailed information, we hope to encourage them to take part in the social debate on this matter.



Figure 41 – De Bergemeesters: new approach for school visits

2. Media Coverage

In 2017 EURIDICE's responsible for Communications Jan Rypens and ONDRAF/NIRAS's spokeswoman Evelyn Hooft took part in a CANVAS documentary series called "WATT" (Figure 42). This series comprised six episodes, with the emphasis on the current use and future perspectives of different energy sources. The third episode, focusing on nuclear energy, was broadcast on 1 May 2018. Interviews with Evelyn Hooft and Jan Rypens in the HADES underground research laboratory were used to introduce the topic of highly radioactive waste, with geological disposal as the long-term management strategy for this waste.



Figure 42 – De Bergemeesters: new approach for school visits

¹ Play on words, as "Burgemeester" is Dutch for Mayor and "bergen" refers to disposal.

3. Newsletter

In 2018 a third newsletter was produced on the PRACTAY Heater test to highlight the publication of the second technical and scientific report entitled "The PRACTAY Heater test after two years of the stationary phase" (Figure 43). This report provides an initial evaluation of the objectives of the PRACTAY Heater test and devotes considerable attention to a comparison of the observations with the prior numerical predictions. These newsletters inform all stakeholders of EIG EURIDICE about the evolution and milestones of EURIDICE's main research project.

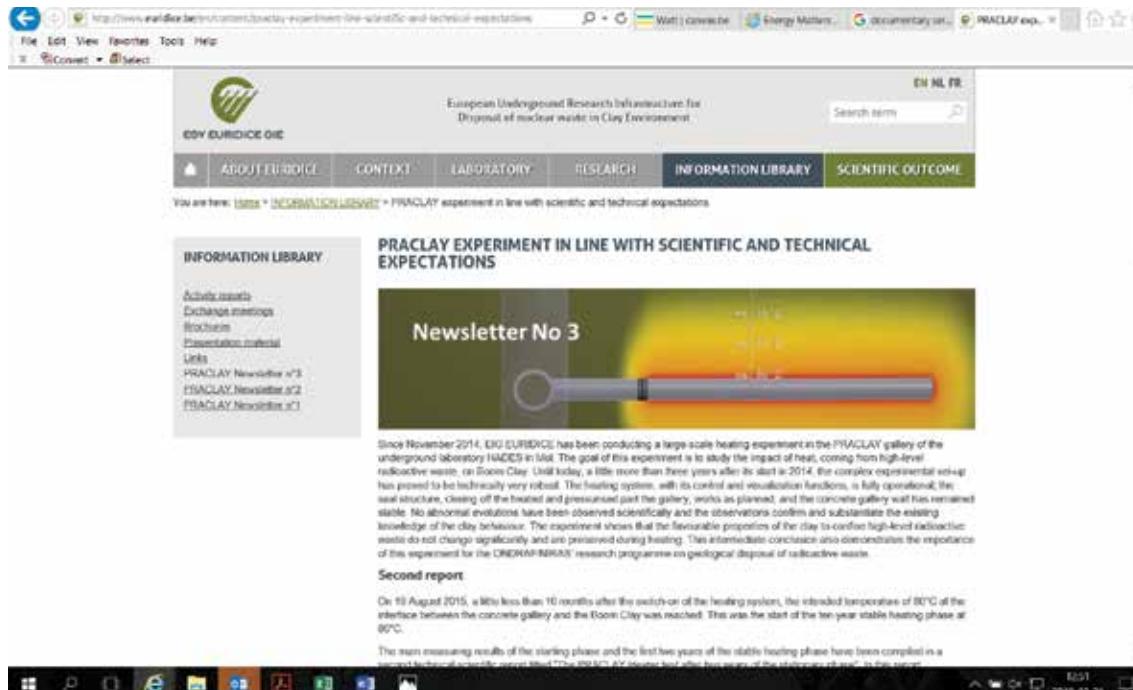


Figure 43 – Third newsletter on the PRACTAY Heater test

4. Participation in external events, conferences and meetings

Team members of EIG EURIDICE took part in national and international meetings and events on several occasions in 2018.

On 27 April 2018, Arnaud Dizier presented an update of the PRACTAY Heater test during a lunch talk at SCK•CEN, entitled "PRACTAY Heater Experiment: 2 years of heating the clay at 80°C". These lunch talks are an opportunity for SCK•CEN to inform its staff about the ongoing research projects in which they are involved.

Guangjing Chen gave a presentation on the Excavation Damaged Zone (EDZ) and its evolution in Boom Clay during the 28th NEA Clay Club meeting in Paris that was organised from 25 to 27 September 2018. He presented the same topic at SCK•CEN during the quarterly meeting of the Environment, Health and Safety Institute on 26 November 2018.

During the "7th China Symposium on Underground Waste Disposal & International Workshop on Radioactive Waste Disposal" on 24-26 August, an international session on the THMC Coupling Process and Gas Transport in Geological and Engineered Barriers was jointly organised by Lille University, ANDRA, CNNC's Beijing Research Institute of Uranium Technology (BRIUG), Hohai University and Tongji University. During this session, Xiangling Li gave a presentation as a guest speaker entitled "Multi scale investigation of the Boom Clay THM behaviour at the Belgian URL HADES (in the context of geological disposal of HLW)".

From 3 to 7 September 2018, the IAEA Technical Meeting on the compendium of results of research, development and demonstration activities carried out at underground research facilities for geological disposal was held in Vienna, Austria. During this meeting, Xiangling Li presented "The roles of the URL HADES in the Belgian RD&D program on radwaste geological disposal".

Scientific output





Reports and Papers

Areias L., Troullinos I., Verstricht J. – *CLIPER Instrumentation Assessment. Review and performance assessment of monitoring technologies used in the CLIPER instrumentation set-up* – EUR 18-111. ESV EURIDICE GIE, Mol, Belgium, 2018. 74p. [Report]

Dizier A. – *Thermal analysis of C-Waste geological disposal facility in clay formations* – EUR 18-010. ESV EURIDICE GIE, Mol, Belgium, 2018. 65 p. [Report]

Dizier A. – *Thermo-hydro-mechanical modelling of a C-Waste geological repository* - EUR 18-013. ESV EURIDICE GIE, Mol, Belgium, 2018. 53 p. [Report]

Dizier A., Chen G., Li X. – *State of the art: Thermo-hydro-mechanical behavior of the Boom Clay* – EUR 18-011. ESV EURIDICE GIE, Mol, Belgium, 2018. 109 p. [Report]

Li X. – *Activity Report 2017* - EUR 18-106. ESV EURIDICE GIE, Mol, Belgium, 2018. 59p. [Report]

Posters and Presentations

Babaei S., Seetharam S., Muehlich Uwe., Areias L., Steenackers G., Craeye B. - *Modeling of Drying Shrinkage in Concrete - A Multiscale Poromechanics Approach*. RILEM-week 2018, Delft, Netherlands [Presentation]

Chen G. - *EDZ and its evolution in Boom Clay*. 28th NEA Clay Club Meeting 24th September 2018, Paris, France. [Presentation]

François B., Nève J., Levasseur S., Dizier A., Gérard P. - *Hydro-Mechanical Modelling of the Boom Clay Excavation, Convergence and Contact with Concrete Lining*. International Symposium on Energy Geotechnics, Lausanne, Switzerland [Presentation]

Gérard P., Nève J., Levasseur S., Dizier A., François B. - *Clay-support interactions for geological radioactive waste disposal*. Second International Workshop on the Finite Element Code, Delft, Netherlands [Presentation]

Li X. - *The roles of the URL HADES in the Belgian RD&D program on radwaste geological disposal*. Technical Meeting on the Compendium of Results of Research, Development and Demonstration Activities Carried out at Underground Research Facilities for Geological Disposal, 3-7 September 2018, Vienna, Austria [Presentation]

Li X. - *Multi-scale investigation of the Boom Clay THM behaviour at the Belgian URL HADES (in the context of geological disposal of HLW)*. 7th China Symposium on Underground Waste Disposal & International Workshop on Radioactive Waste Disposal, 24-26 August 2018, China [Presentation]

Proceedings

Babaei S., Seetharam S., Muehlich U., Areias L., Steenackers G., Craeye B. - *Modeling of Drying Shrinkage in Concrete - A Multiscale Poromechanics Approach*. Symposium on Concrete Modelling (CONMOD2018). RILEM Publications, 2018. pp. 165-168 [Proceedings]

François B., Nève J., Levasseur S., Dizier A., Gerard P. - *Hydro-Mechanical Modelling of the Boom Clay Excavation, Convergence and Contact with Concrete Lining*. Energy Geotechnics. Springer, 2018. pp. 418–425 (Springer Series in Geomechanics and Geoengineering) [Proceedings]

List of acronyms

ANDRA	Agence Nationale pour la Gestion des Déchets Radioactifs (FR)
BDT	Below Drilling Table
BGL	Below Ground Level
BRIUG	Beijing Research Institute of Uranium Technology
CAEA	China Atomic Energy Authority
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
CNNC	Chinese National Nuclear Corporation
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
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
URF	Underground research facility



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.

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