2020

Activity Report

ESV EURIDICE EIG

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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 manages and operates the HADES underground research laboratory (URL), carries out research and development activities for the geological disposal of radioactive waste in deep clay formations and communicates about its activities. This Activity Report provides a comprehensive overview of the main developments and results relating to these statutory tasks of EIG EURIDICE in 2020.

With the new Statutory Rules and Internal Rules and Regulations of EIG EURIDICE approved in 2019 by the Boards of Management of SCK CEN and ONDRAF/NIRAS, continued collaboration between SCK CEN and ONDRAF/NIRAS through the EIG until 2045 was established. The new rules ensure continuity of the EIG's activities, emphasising the importance of knowledge management for EIG EURIDICE's activities and tasks, and the key role of the HADES URL in this respect for the ONDRAF/NIRAS geological disposal programme. With a view to the constituent members' continued collaboration through EIG EURIDICE and future RD&D use of the HADES URL, the Management Board of EIG EURIDICE decided to go ahead with the refurbishment of shaft 1, which dates back to the early 1980s. After the public tender contracts for the project were awarded in 2019, on-site works started in 2020. Following removal of the old hoisting system and installation of a temporary one, the shaft was completely renovated. The new building housing the hoisting machine was also erected at the same time. The project was delayed by a few months, partly because of COVID-19 restrictions, and is due to end, with the new hoisting system fully operational, by mid-2021. As a result of the significant modifications to the facility and because of changes in the regulatory requirements, EURIDICE has applied to the municipality of Mol for a new operating licence.

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 fifth year of heating at 80°C was successfully completed in 2020, bringing the experiment to mid-term. Over these first five years, the experimental set-up has proved to be robust and reliable: the hydraulic seal and the heating system are performing flawlessly, as designed and as expected, and the multiple measuring instruments and sensors in and around the PRACLAY gallery are accurately monitoring all important aspects of the Heater test and its evolution over time (PRACLAY gallery, concrete lining, seal structure, clay). All the scientific findings and results obtained since the start of the Heater test show that the

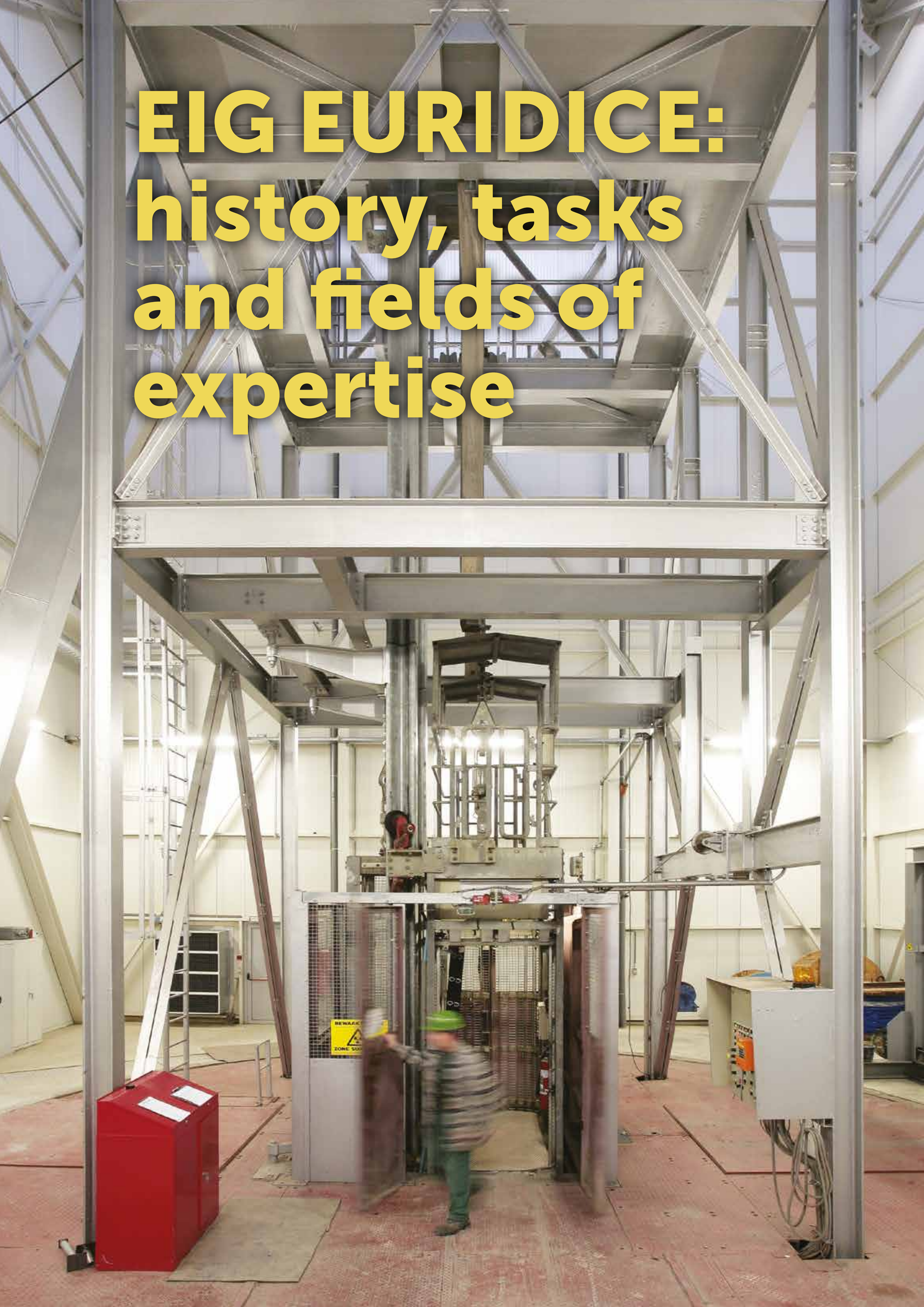
temperature rise in the clay does not significantly alter its structural integrity or its ability to act as an effective barrier to a disposal system. Assessing this in a sound scientific and transparent manner is a key objective of the experiment. EURIDICE is therefore publishing the intermediate results and observations of the PRACLAY Heater test in peer-reviewed scientific journals.

Due to the refurbishment of shaft 1 and the COVID-19 pandemic, EURIDICE welcomed only 331 visitors to HADES and the permanent exhibition in 2020. Instead, a great deal of time was devoted to formulating EURIDICE's communication strategy for the next few years in relation to the new communication centre Tabloo, which will open in Dessel in 2022. In that context, EURIDICE also supported the development of specific modules of ONDRAF/NIRAS's brand-new exhibition on radioactive waste management.

Many people will remember 2020 as the year COVID-19 took over the world. For EURIDICE, it also meant the start of the refurbishment of shaft 1, 40 years after the first construction works. Moreover, the PRACLAY Heater test successfully reached mid-term in 2020, marking an important milestone for the research programme on geological disposal. Plenty of reasons for EIG EURIDICE and its two constituent members to prepare for the events to showcase these milestones, when the health situation allows us to do so in a convivial manner. We will keep you informed of developments.

Marc Demarche, chairman of the board of EIG EURIDICE

EIG EURIDICE: history, tasks and fields of expertise



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

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

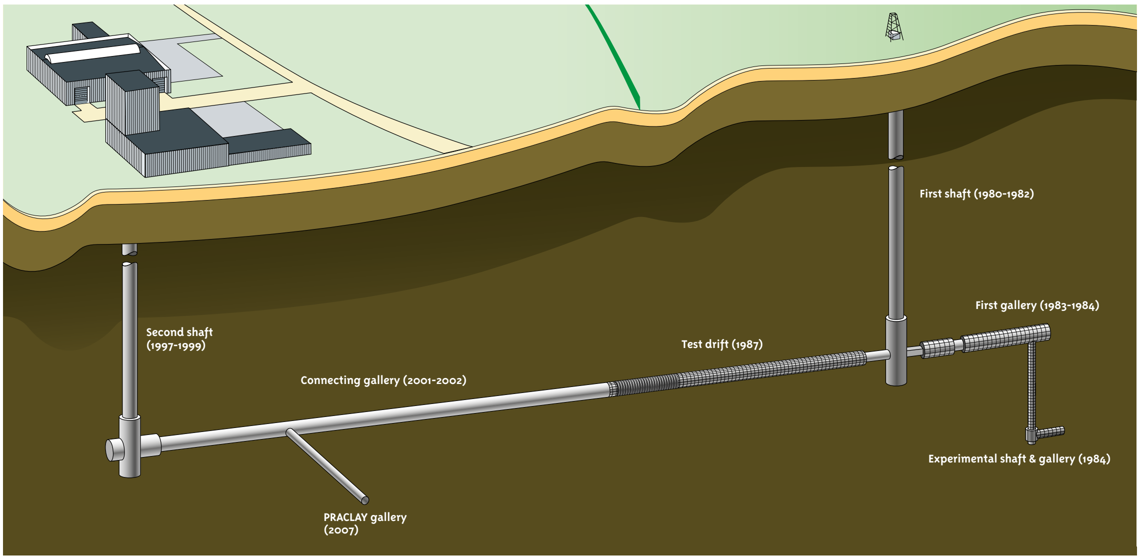


Figure 1 – The underground research laboratory HADES (High-Activity Disposal Experimental Site)

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

- Coordination and execution of RD&D projects with the aim of demonstrating the safety and feasibility of radioactive waste disposal (incl. the PRACLAY project).
- Coordination and valorisation of the use of the HADES underground research laboratory (URL) for RD&D purposes.
- Management and preservation of the scientific and technical knowledge obtained by EIG EURIDICE and in the HADES URL.
- Communication about its own activities, in dialogue with its constituent members, including the organisation of visits to the HADES URL.
- Management and operation of the HADES URL and all the installations situated on the land for which EIG EURIDICE has a building lease.
- The possible realisation and valorisation of other research projects concerning the management of radioactive waste with a view to supporting the technical and scientific programmes of its constituent members.
- The possible realisation and valorisation of other research projects concerning the management of radioactive waste for which EIG EURIDICE enters into partnerships or other agreements with third parties, in so far as this does not jeopardise the above statutory tasks.

After 40 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.

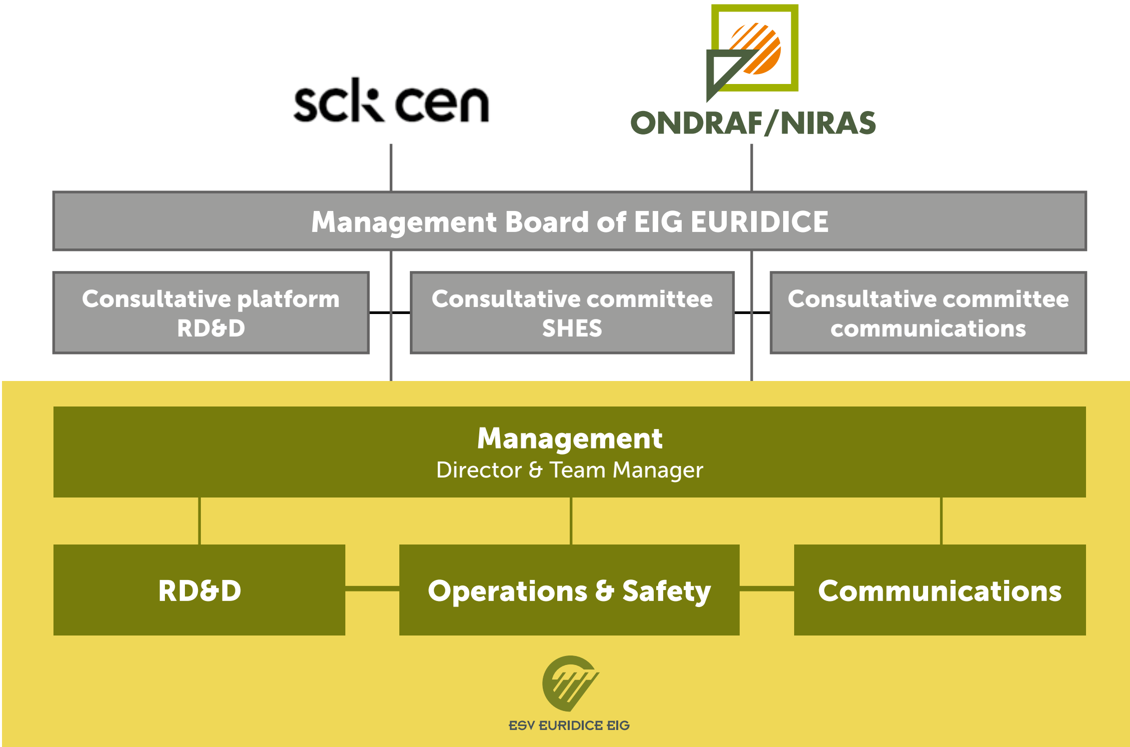
EIG EURIDICE's first area of expertise has changed significantly over the years, with excavation and construction of the HADES URL evolving from semi-manual and slow to industrial, using tailor-made tunnelling machines. The tunnelling techniques used to excavate in poorly indurated deep clay layers, 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 would 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 caused 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 EDZ. Proper understanding of the coupled THM processes in a clay host rock around a potential repository is essential so as to determine to what extent these processes could affect the capacity of the clay to contain radioactive substances and to isolate 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 published 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 for the disposal of high-level and long-lived waste 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 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, the team manager and the director of EURIDICE attend meetings in an advisory capacity. The government commissioners of both members are invited to attend the meetings of the board.

Figure 2 – Meeting of the management board in presence of SCK CEN's government commissioner Martial Pardoen

The board members as at the end of 2020 are as follows (June 2019 - June 2022):
- Marc Demarche, chairman, director-general of ONDRAF/NIRAS
- Philippe Lalieux, director Long-term Management ONDRAF/NIRAS
- Eric van Walle, director-general of SCK CEN
- Hildegarde Vandenhove, director of the Environment, Health and Safety institute of SCK CEN

Responsibility for day-to-day management of EURIDICE lies with the **director**, who is appointed by ONDRAF/NIRAS. The director is assisted by the **team manager**, appointed by SCK CEN.

The board of the EIG is advised by three internal bodies: (1) the consultative committee on safety, health, environment & security, (2) the consultative committee on communications and (3) the consultative platform on RD&D. These bodies support EIG EURIDICE in its activities and facilitate consultation and collaboration with its constituent members in the respective fields. They are composed of representatives of the constituent members, representatives of EIG EURIDICE, and the director and/or team manager of EIG EURIDICE. The committees identify the objectives and priorities of EIG EURIDICE in each of the three fields. They meet on a regular basis and report to the board of directors of EIG EURIDICE.

With the approval of the new **Statutory Rules** for EIG EURIDICE in 2019, the lifetime of the EIG has been extended from 2025 until 2045. Concerning its statutory tasks, greater emphasis is placed on knowledge management and scientific valorisation of the RD&D activities of EIG EURIDICE and in the HADES URL.

EIG EURIDICE has been ISO-certified to the ISO 9001 standard for Quality Management since 2007. The current certificate is valid until 23 September 2021. On 18 September 2020 an external follow-up audit according to ISO 9001:2015 was performed by DNV-GL with the focus on General Management, Communications, RD&D and Measurements & Monitoring. During 2020, in interaction with both constituent members, specific efforts were made to define new strategic and operational objectives for the years ahead (2021-2025). The next step will be to devote special attention to monitoring key processes with a view to continuous improvement. The recertification audit will take place in 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.

At the end of 2020 the EURIDICE team was composed of the following people:

Director:
Peter De Preter

Team manager:
Mieke De Craen

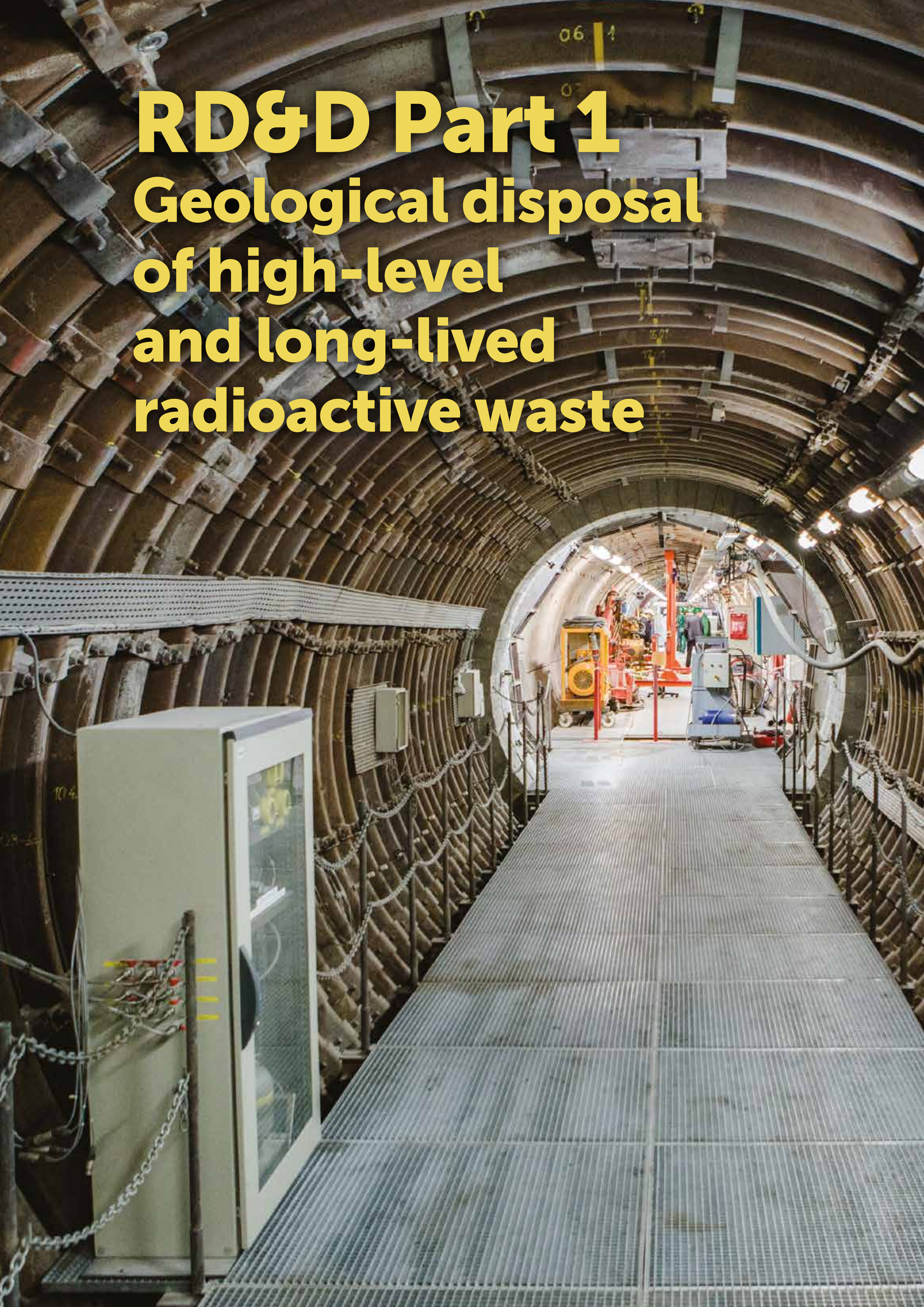
Management assistant:
Caroline Poortmans

RD&D process:
Xiang Ling Li - coordinator
Arnaud Dizier - collaborator
Guangjing Chen - collaborator
Dries Nackaerts - collaborator
Jan Verstricht - collaborator

Operations and safety process:
Kevin Schuurmans - manager
Luc Mariën - project engineer
Dries Nackaerts - collaborator
Christian Lefèvre - collaborator
Johan Peters - collaborator
Bert Vreys - collaborator

Communication process:
Jan Rypens - coordinator
Els van Musscher - collaborator

RD&D Part 1
Geological disposal of high-level and long-lived radioactive waste



In 2020, EIG EURIDICE's RD&D activities related to geological disposal mainly focused on the PRACLAY Heater test. Section 1 of RD&D Part 1 provides an overview of the main observations regarding the test since switching on the heating system on 3 November 2014 up until the end of 2020, based on measurements from the numerous sensors installed in the PRACLAY gallery, the seal, the concrete lining and in instrumented boreholes around the PRACLAY gallery. By the end of 2020 the PRACLAY Heater test had been running for more than six years. The experimental set-up is still working perfectly. The test components are evolving as expected. No negative impact on the clay as a natural barrier has been observed.

Over the years, we have constantly sought to improve interpretation of the PRACLAY Heater test results by means of modelling, which enables us to refine the thermo-hydro-mechanical (THM) characterisation of the Boom Clay and confirm what we know about its THM behaviour. In 2020 efforts were also made to publish our research results on this large-scale, long-term in-situ Heater test in highly ranked journals. This resulted in three papers, one on the initial observations of the in-situ thermo-hydro-mechanical (THM) behaviour of the Boom Clay (accepted), a second on numerical modelling of the large-scale in-situ PRACLAY Heater test in the Boom Clay (under review), and a third on the thermal characterisation of the Boom Clay based on numerical interpretation of both a small-scale (ATLAS IV) and a large-scale Heater test (PRACLAY) (to be submitted). Moreover, an integrated report on the scientific interpretation of the PRACLAY Heater test was approved in-house and will be submitted to ONDRAF/NIRAS in 2021. This report summarises the main observations and includes the stepwise improvement in the numerical interpretation of the test measurements and resulting refinement of the THM parameters of the Boom Clay.

In parallel with the PRACLAY Heater test, a general thermo-hydro-mechanical-chemical (THMC) characterisation programme on the Boom Clay is being run. Part of this programme is covered by several PhD research projects. EIG EURIDICE is involved in supervising these PhD projects (Section 6). This is important to reinforce the link with academic research.

In 2020 another focus of attention was sensor performance assessment (Section 3). 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 galleries of HADES. A closer investigation of the instrumentation can therefore give us valuable insight into long-term sensor performance 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. The first study, from 2015 until 2018, dealt with the performance assessment of the instrumentation installed as part of the CLIPEX project. Based on this study, a paper was written in 2020 that will be submitted to a journal in 2021. The second study began in 2018 and looked at the PRACLAY in-situ experimental set-up. As work in 2019 was delayed due to other tasks, the study was resumed in 2020. This resulted in an extensive report, to be delivered to ONDRAF/NIRAS in 2021.

Section 5 gives an overview of EURIDICE's international activities. In 2020 EURIDICE contributed to the European Joint Programme on Radioactive Waste Management and Disposal (EURAD). EURIDICE is involved directly in Work Package (WP) HITEC to study the influence of temperature on clay-based material behaviour, and indirectly in WP GAS studying the mechanistic understanding of gas transport in clay materials. For WP GAS, EURIDICE provides scientific and technical support to SCK CEN's Waste and Disposal (W&D) expert group.

EURIDICE also contributed to the IAEA's *Compendium of Results of RD&D Activities carried out at Underground Research Facilities (URFs) for Geological Disposal*. This contribution is important to preserve the scientific knowledge that has been accumulated over the past 40 years. In addition, it increases the international visibility of the RD&D carried out at the HADES URL.

1. The PRACLAY Heater test

The **PRACLAY project** was launched in 1995 to demonstrate the feasibility of the disposal of high-level, heat-producing vitrified radioactive waste or spent fuel in poorly indurated clay such as the Boom Clay. With this project, EIG EURIDICE is making an important contribution to the ONDRAF/NIRAS programme for long-term management of long-lived and high-level radioactive waste.

The PRACLAY project consists of several sub-projects and 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.

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

For the purpose of the Heater test, part of the PRACLAY gallery (30 m) has been closed off with a seal structure and will be heated for a period of 10 years at a temperature of 80°C at the interface between the gallery lining and the clay. The Heater test has been designed in such a way that it is representative of the conditions that would be expected in a high-level waste repository for both vitrified high-level waste and spent fuel. After the construction of the PRACLAY gallery in 2007 and the design and installation of the seal (2007-2010), installation of the heating system started in 2010 (primary heater) and was completed in 2014 (secondary heater). A detailed report about the design, preparation and installation of the PRACLAY 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 the secondary heating system. After a successful test phase, it was decided at the beginning of 2015 to continue heating. The target temperature of 80°C at the interface between the gallery lining and the clay was reached on 18 August 2015, marking the end of the start-up phase. A detailed report on the experimental evolution during the start-up phase was published in 2016 (EUR_PH_16_025).

Since then, the power of the heating system has been systematically adjusted to maintain the temperature at this interface constant at 80°C, marking the start of the stationary phase of the Heater test. A constant flow of data is generated by an extensive network of sensors installed in and around the PRACLAY gallery, and compared with the predictions made by modelling. A second report (EUR_PH_17_043) was published 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 PRACLAY Heater test. The numerical interpretation of the data generated by the PRACLAY Heater test is constantly being improved. In 2020 an integrated report was prepared that summarises the main observations and includes the stepwise improvement in the numerical interpretation of the test measurements and resulting refinement of the thermo-hydro-mechanical parameters of the Boom Clay. The report will be published in 2021.

By the end of 2020 the PRACLAY Heater test had been successfully running for more than six years. The experimental set-up is still working perfectly. The test components are evolving as expected, confirming the ability of the clay to withstand heating.

1.1. Test set-up

The different parts of the PRACLAY Seal & Heater experimental set-up are shown in Figure 3. The heating system is installed in a 30-metre-long section of the PRACLAY gallery. This section is backfilled with sand, closed from the accessible part of the PRACLAY gallery by a seal structure and saturated with water.

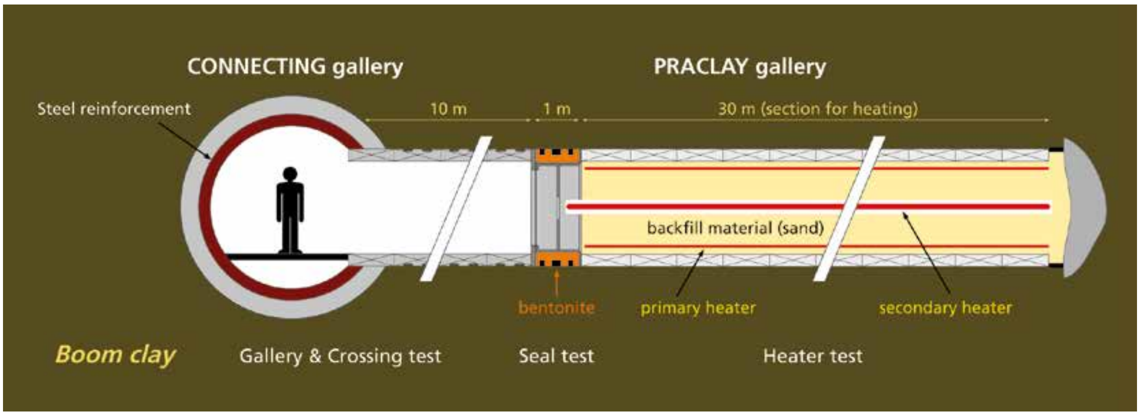


Figure 3 – Design of the PRACLAY experiment

HEATING SYSTEM

The **heating system** consists of a primary heater, attached to the gallery lining, and a secondary heater, which is placed in a central tube that rests on a support structure. Both of these are electrical heaters. Figure 4 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 4 – 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 5). Each section is equipped with two heater elements, ensuring 100% redundancy of the system.

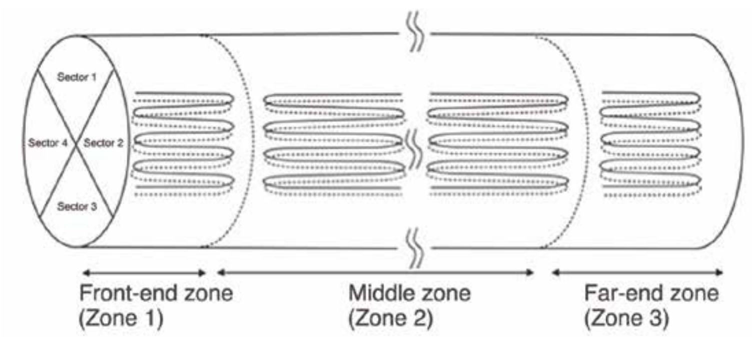


Figure 5 – The primary heating system is composed of three zones, each divided into four sections

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, if needed.

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 6).

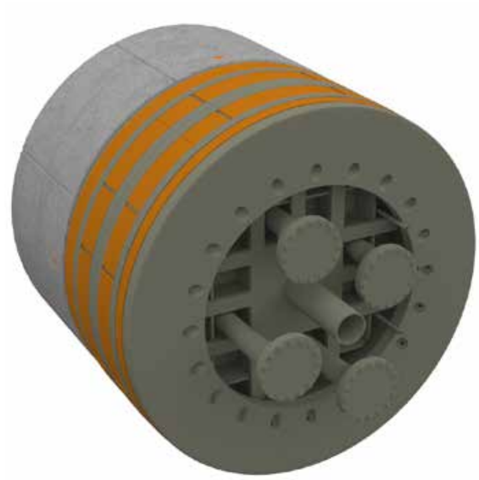


Figure 6 – 3D view of the seal with a central steel cylinder and an annular ring of bentonite (orange) against the clay

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 and the interaction with the Boom Clay. An initial dry density of 1.8 tonnes/m^3 was selected. Secondly, the bentonite needs to be sufficiently hydrated. The bentonite seal has been hydrated since its installation in January 2010 by pore water coming from the Boom Clay and by water injected through filters placed on the outer surface (extrados) of the steel cylinder since April 2010. Different kinds of instruments were incorporated into the bentonite rings during installation to monitor the water injection rate, as well as stress (swelling pressure) and pore water pressure in the bentonite and in the Boom Clay around the seal. The instruments are grouped into sections A, B and C (Figure 7).

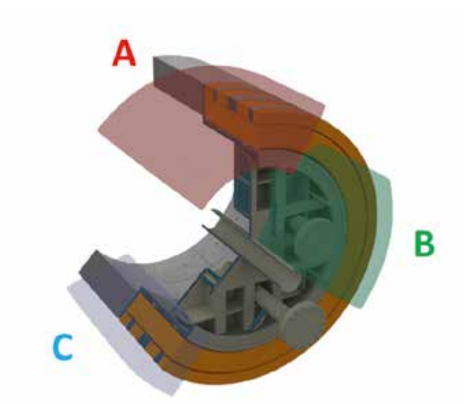


Figure 7 – Various instruments inside the bentonite, grouped into sections A, B and C

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 8). 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 were similar to that of the undisturbed Boom Clay.

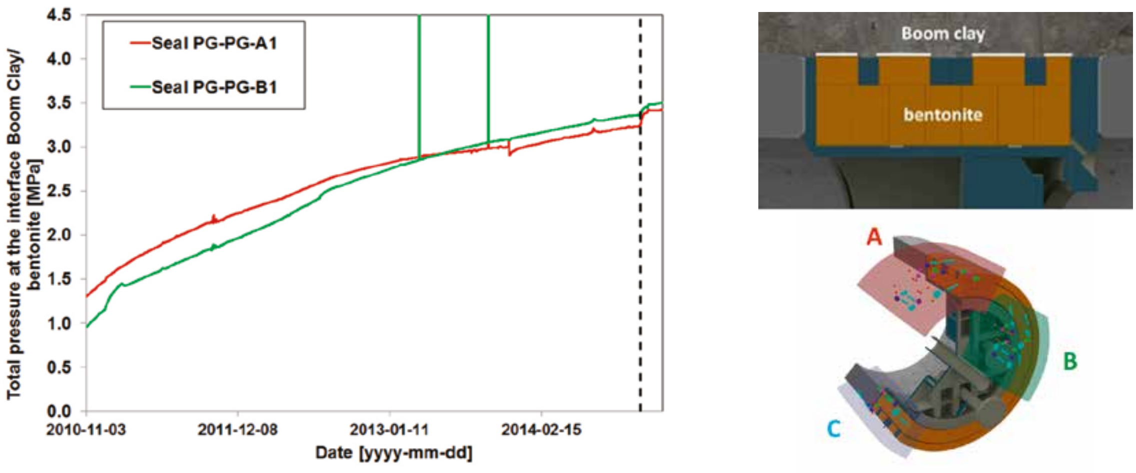


Figure 8 – Radial stresses measured at the interface between the bentonite and the Boom Clay sidewall (white line in insert), for sections A, B and C. The vertical dashed line marks the date of the switch-on.

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, generation of a daily Safety Report, and an extensive graphical module to generate both time evolution and spatial profiles of measured variables.

The functionality of the sensors is monitored primarily by analysis of the sensor data. This occurs both manually and automatically, through alarm limits, set in the database and the heater control system.

The reliability of the pore water pressure measurements is further increased by a yearly calibration of the pressure transmitters. Ten pressure transmitters measuring low pressures (from filters next to the Connecting gallery lining) have been replaced by new transmitters with a lower measurement range to increase measurement resolution and accuracy.

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. 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 prior to the start of the Heater test to specify the follow-up of the test, define the action plan in case of unexpected events or deviating evolution of the test components, and clearly outline and assign the different responsibilities with respect to safety, scientific objectives and technical aspects, such as maintenance and checks.

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 Heater test, predictive modelling of the PRACLAY Heater test was performed, the so-called 'numerical predictions', considering different scenarios – normal and altered (i.e. deviating from the expected evolution). The objectives of these numerical predictions are:

- 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 gain insight into how the Heater test is expected to evolve.
- 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.
- To determine the power input for the heater control system during the heating phase.

Since switch-on of the heating system, numerical modelling has received constant attention:

- To adjust the primary heater power for the manual input in the heater control system during the stationary phase in order to maintain the designed thermal boundary condition of 80°C at the interface between the lining and the clay.
- To improve interpretation and understanding of the measurements and observations of the Heater test, and to refine the THM parameters of the Boom Clay.

1.3. Observations since the switch-on until the end of 2020

The primary heating system was switched on on 3 November 2014. 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'. Since August 2015 the temperature at the contact between the lining and the Boom Clay has been maintained at 80°C, marking the start of the stationary phase of the Heater test.

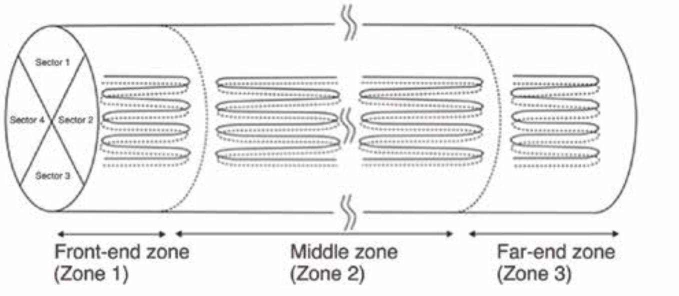
The main results from the Heater test since the switch-on in November 2014 up until the end of 2020 are presented in this section.

EVOLUTION OF THE TEST-CONTROL PARAMETERS

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 9 and Figure 10). 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 9 and Figure 10. 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.



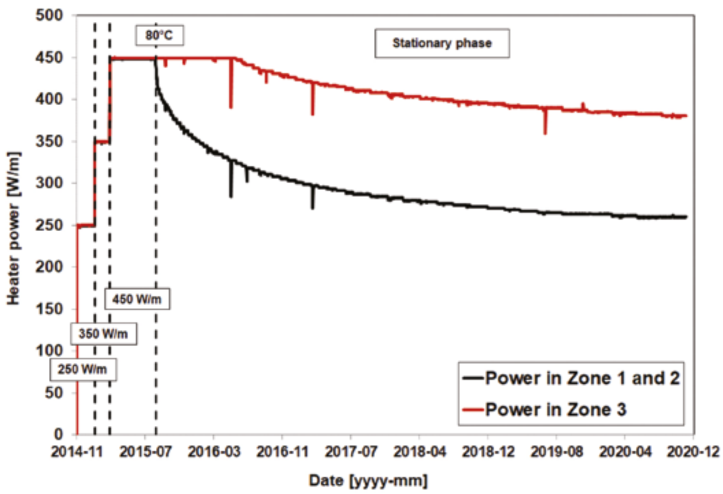


Figure 9 – Evolution of the power in watts per metre (W/m) in the three zones. The power in Zones 1 and 2 was decreased once the temperature in Zone 2 reached 80°C (measured by T_{int_1}). The power in Zone 3 was decreased with a delay of a couple of months once Zone 3 reached 80°C (measured by T_{int_2}).

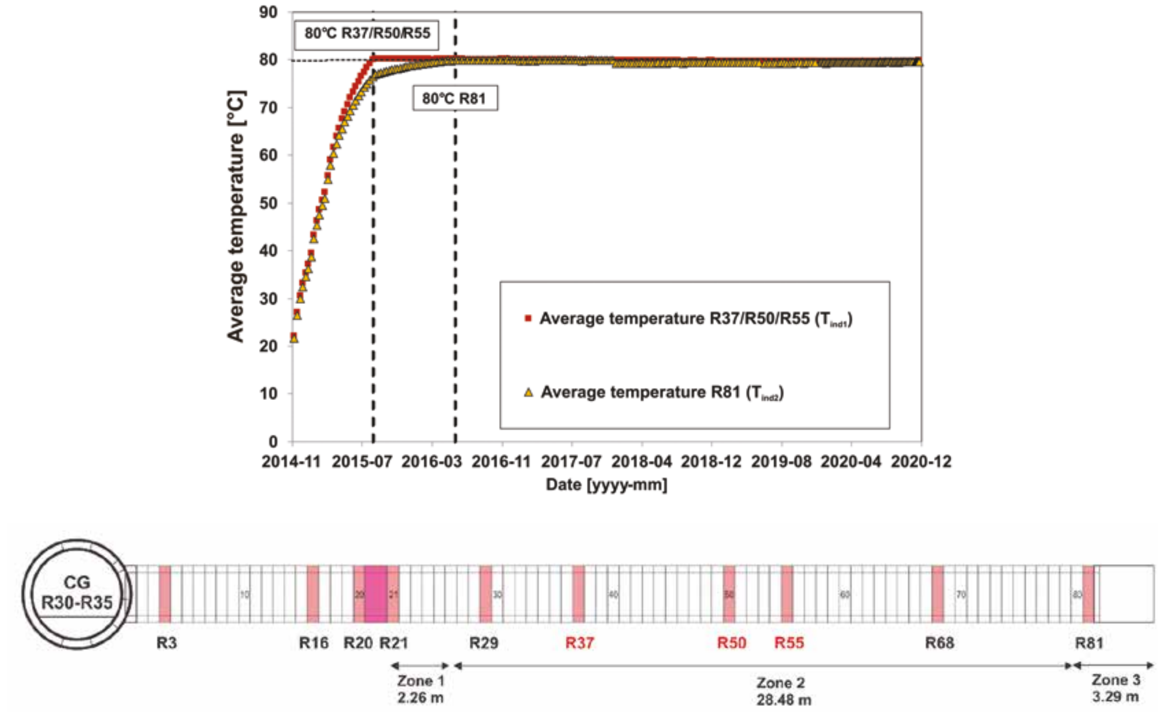


Figure 10 – Average temperature evolution measured using the extrados sensors in R37, R50 and R55 (T_{int_1}) and R81 ($_{Tint\_2}$)

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 11, 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.

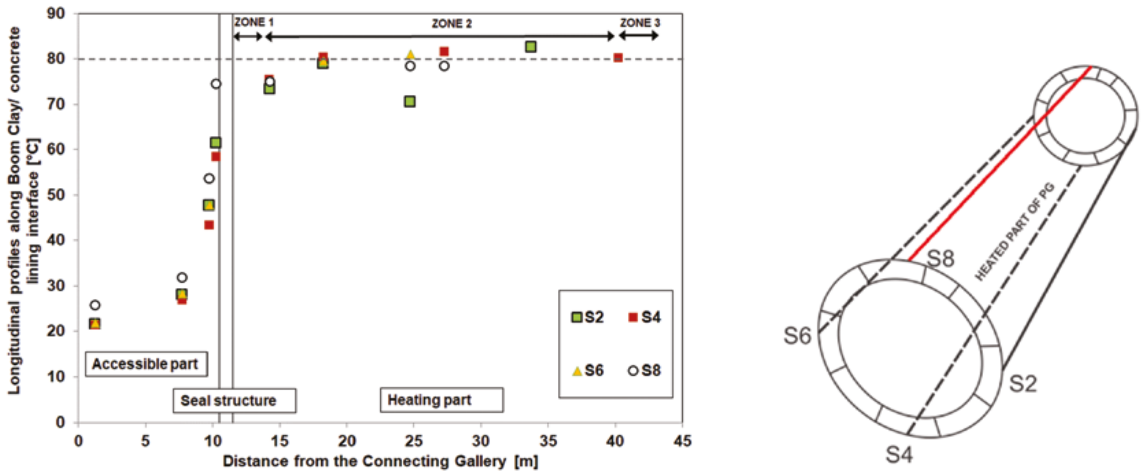


Figure 11 – Longitudinal profiles of the temperature along the extrados of the PRACLAY gallery

Following heating and due to the difference in the thermal expansion 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 of the Boom Clay and relative higher rigidity of the concrete lining), an excess pore water pressure is induced inside the PRACLAY gallery. This rise in pore water pressure in the backfilled part of the PRACLAY gallery is shown in Figure 12. 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 PRACLAY gallery is uniform.

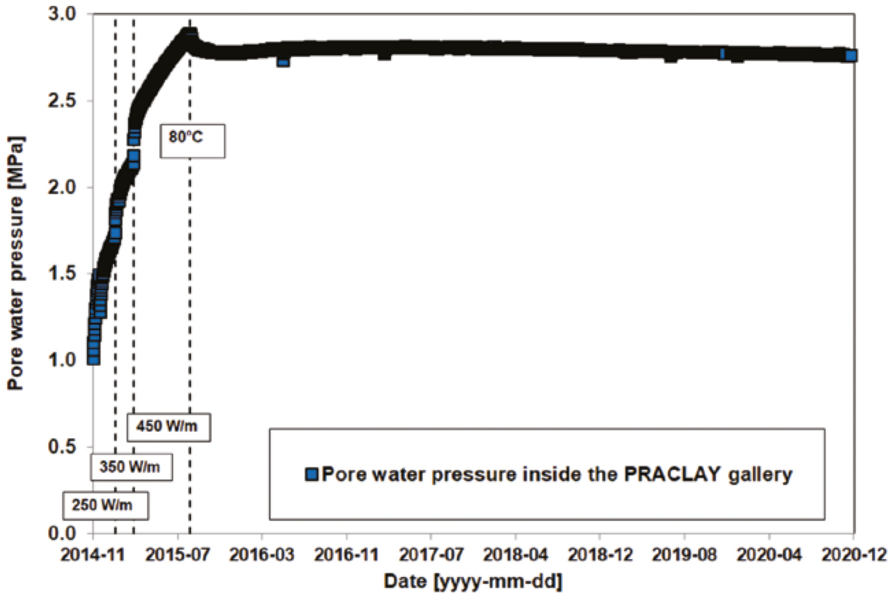


Figure 12 – Pore water pressure evolution in the backfilled part of the PRACLAY gallery

BOOM CLAY RESPONSES

It is well known that natural clay sediments, such as the Boom Clay, are anisotropic. An initial (inherent) anisotropy results from the preferential orientation of clay particles during sedimentation and from subsequent soil diagenesis. This initial anisotropy can be induced or modified later on by coupled thermo-hydro-mechanical (THM) loading paths. The overall anisotropy results in anisotropic heat transfer and water flow (thermal and hydraulic conductivity) and also in anisotropic mechanical behaviour (Young's modulus, cohesion, etc.). Consequently, the THM behaviour of such natural clays is anisotropic.

Studying the anisotropic THM behaviour of the Boom Clay is one of the key objectives of the PRACLAY Heater test. To be able to capture and study the anisotropic response to excavation and heating, instrumented boreholes are installed in directions parallel and perpendicular to the stratification of the Boom Clay, which is sub-horizontal.

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 expansion 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 13).

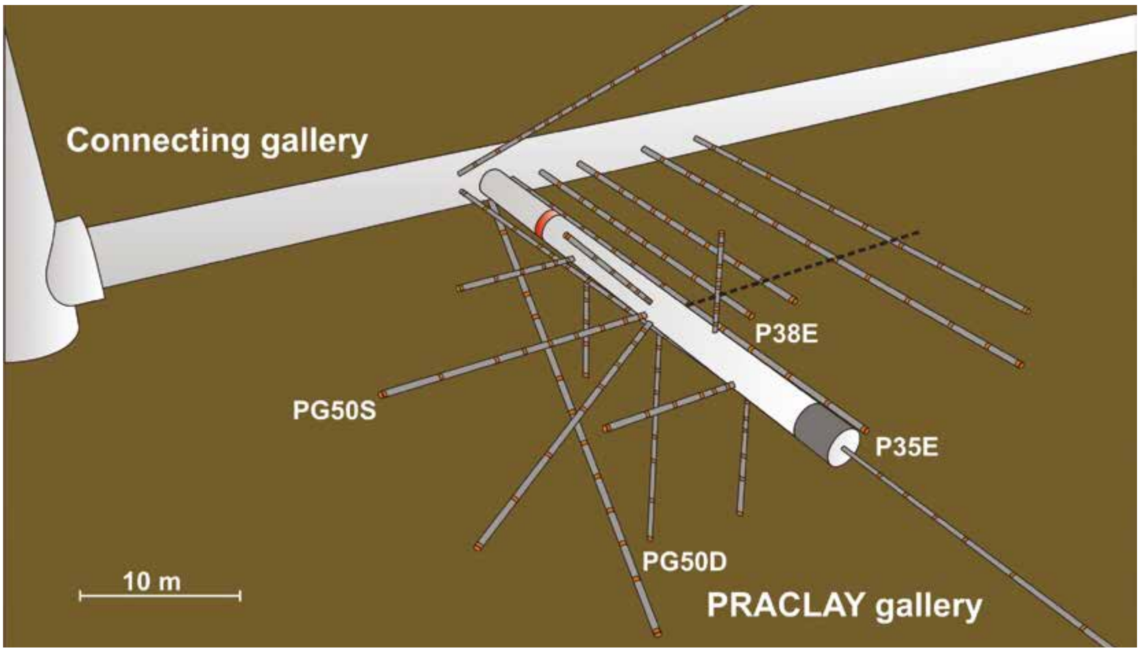


Figure 13 – 3D view of the instrumented boreholes from the PRACLAY gallery and the Connecting gallery

Evolution of temperature and pore water pressure in the vertical and horizontal directions is shown in Figure 14 and Figure 15. After the rapid increase during the start-up phase, temperature and pore water pressure change very slowly. In terms of anisotropic behaviour, direct observation is not straightforward, because it is difficult to find a pair of sensors, either from the Connecting gallery or from the PRACLAY gallery, at the same distance but in different directions, which would enable direct comparison of the measurements (both the temperature and the pore water pressure evolution) in different directions. This is because quite a number of sensors have failed, making observation of the anisotropy of the clay more laborious. In a qualitative way, Figure 14 presents the evolution of the temperature in two directions (vertical and horizontal), from PG50D and from the Connecting gallery boreholes, showing that the temperature rises higher in the horizontal than in the vertical direction. Figure 15 shows the pore water pressure for the same sensors in both directions (vertical and horizontal): it seems that the pore water pressure in the horizontal direction attains higher values, which would be a consequence of the anisotropic properties of the Boom Clay.

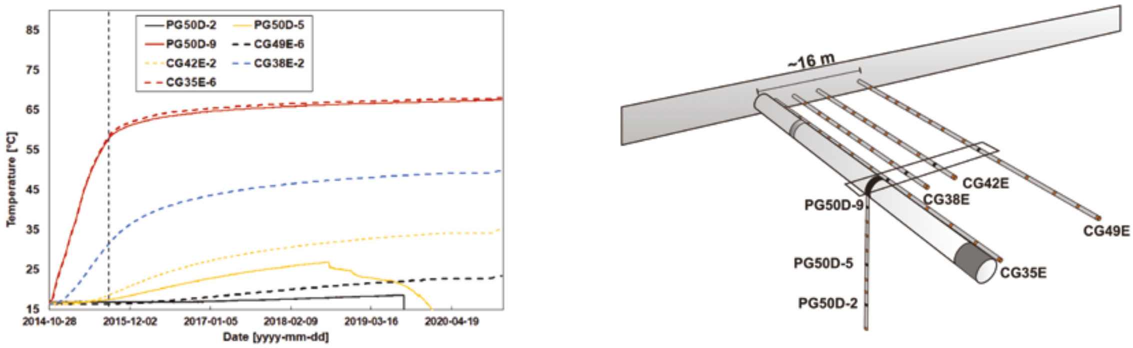


Figure 14 – Comparison between the temperature evolution in two directions (vertical (PG50D) and horizontal (CGXXE))

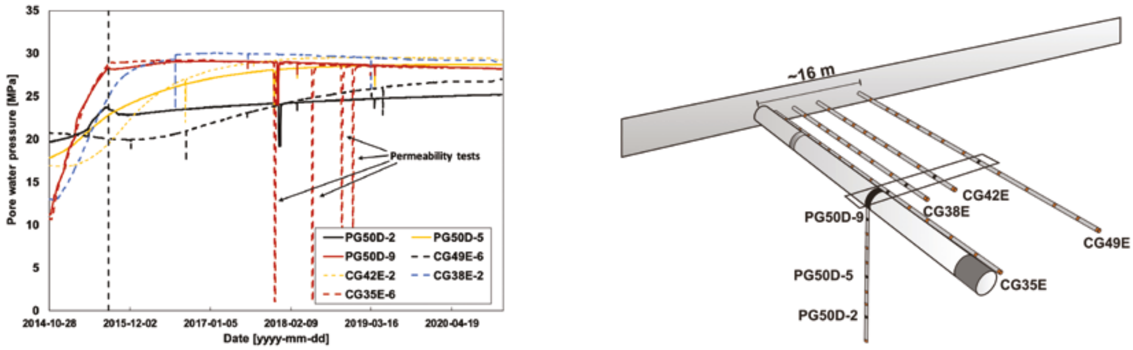


Figure 15 – Comparison between the pore water pressure evolution in two directions (vertical (PG50D) and horizontal (CGXXE))

The evolution of pore water pressure profiles in both horizontal and vertical directions can be seen in Figure 16, and the evolution of the temperature in the horizontal direction in Figure 17.

It was observed that, at the end of 2020, the thermally affected zone had extended to a depth of more than 15 m into the Boom Clay in the horizontal direction (Figure 17). Concerning the evolution of the pore water pressure in the Boom Clay, close to the concrete lining, this 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 16).

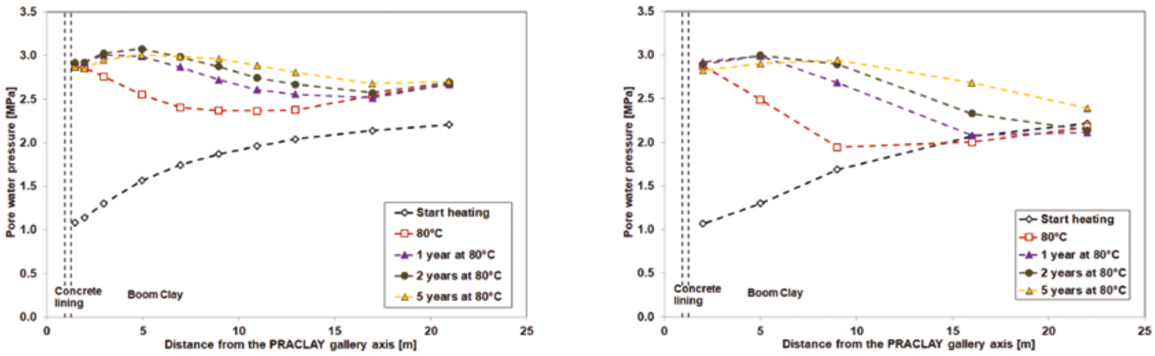


Figure 16 – Evolution of the pore water pressure profiles in different directions at the middle section of the heated part of the PRACLAY gallery

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 a maximum of 2.8 MPa in the deepest part of the borehole, which is also closest to the pore water pressure measured inside the PRACLAY gallery. After this peak, the pore water pressure measured showed a decrease, as observed with the profiles characterising the past two years. As explained previously, the peak in pore water pressure was reached two years ago, marking the start of the dissipation of the pressure into the surrounding environment. This phenomenon was expected from predictive modelling.

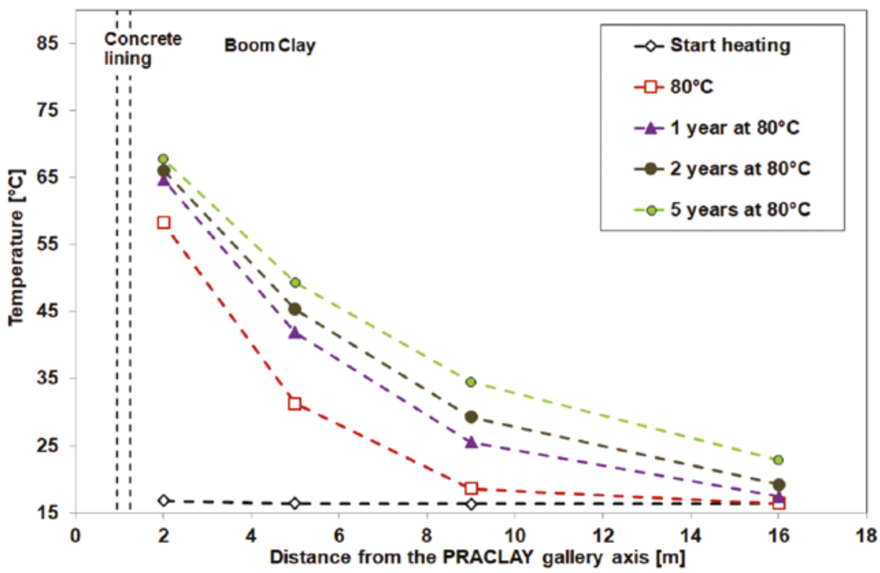


Figure 17 – Temperature profiles in the horizontal direction at the middle section of the heated part of the PRACLAY gallery (measured from boreholes drilled from the Connecting gallery)

Spatial distribution of the temperature and pore water pressure at different times around the PRACLAY gallery is illustrated in Figure 18 and Figure 19. Figure 18 shows the temperature and pore water pressure profiles along CG35E, located approximately 0.75 m from the extrados of the PRACLAY gallery lining. The pore water pressure profile is almost uniform along CG35E (Figure 18b), while the temperature profile shows a slight gradient from the seal to the end part of the PRACLAY gallery (Figure 18a). The pore water pressure profiles in Figure 18b clearly show the hydraulic cut-off by the seal (high pore water pressure gradient around it).

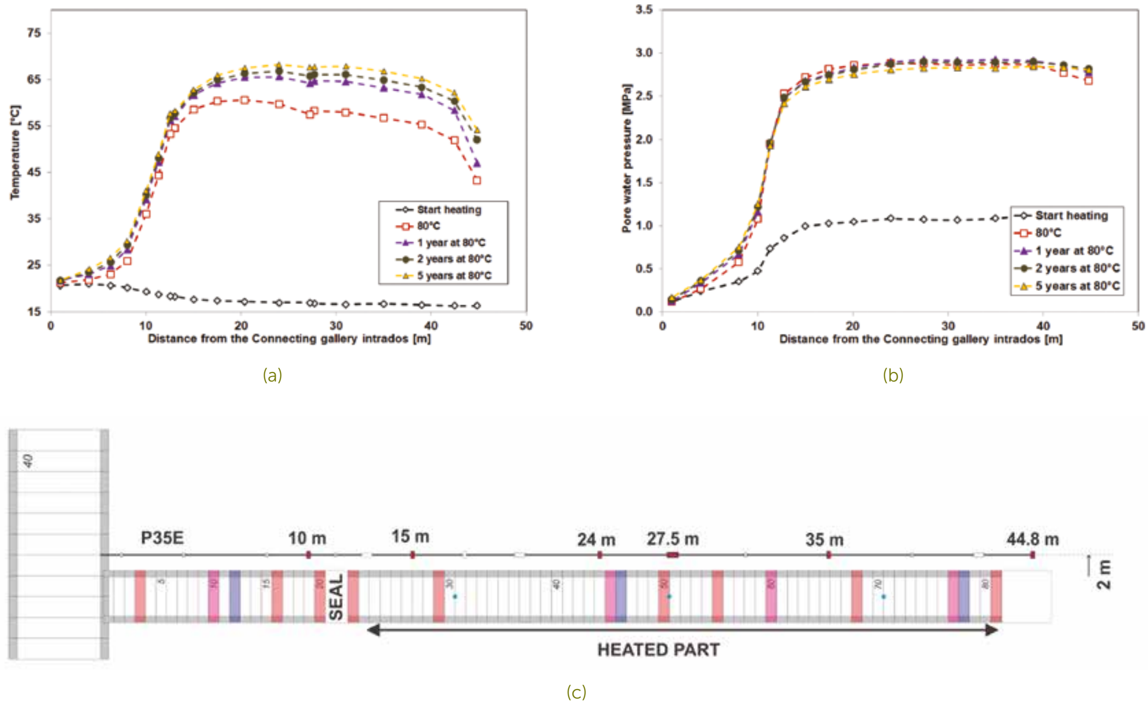


Figure 18 – Temperature and pore water pressure profiles along CG35E

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 CG38E; see Figure 13) can be seen in Figure 19. The pressure in this borehole reached a maximum of 2.8 MPa in the deepest part of the borehole. After this peak, the pore water pressure showed a decrease, as observed in the last two profiles (two and five years at 80°C). As explained previously, the peak in pore water pressure was reached three years ago. This phenomenon was expected from predictive modelling.

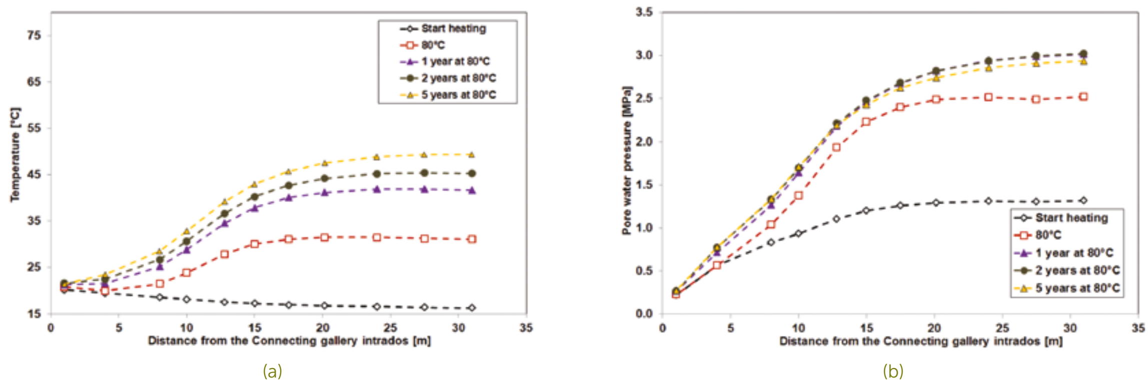


Figure 19 – Temperature and pore water pressure profiles in CG38E

Another way to present the evolution of the pore water pressure is the distribution plots in the horizontal plane containing the Connecting gallery boreholes. The pore water pressure distribution around the PRACLAY gallery can be estimated by a linear interpolation between the monitoring points within the boreholes drilled from the Connecting gallery, respectively with PG30S, PG70S, CG35E, CG38E, CG42E, CG49E and CG55E. Figure 20 shows the distribution of the pore water pressure prior to heating, when the pore water pressure in the future heated section of the PRACLAY gallery is about 1 MPa as a result of the pressurisation of the backfill. The drainage by the Connecting gallery (at atmospheric pressure) and by the PRACLAY gallery can clearly be seen.

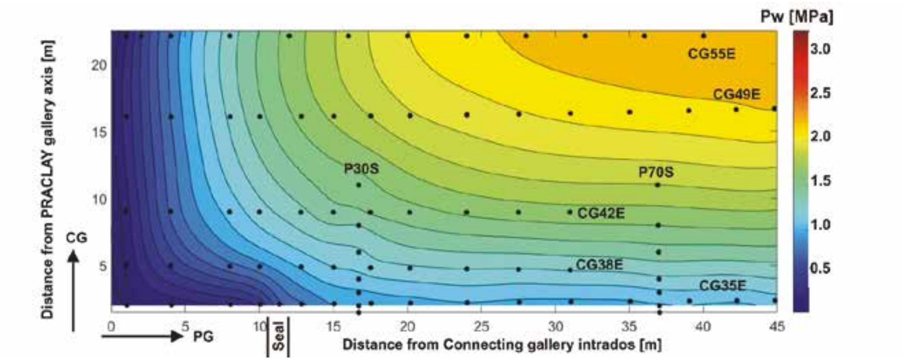
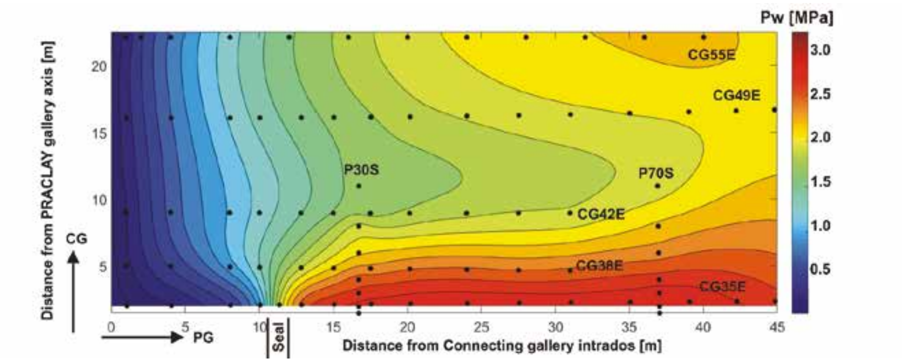
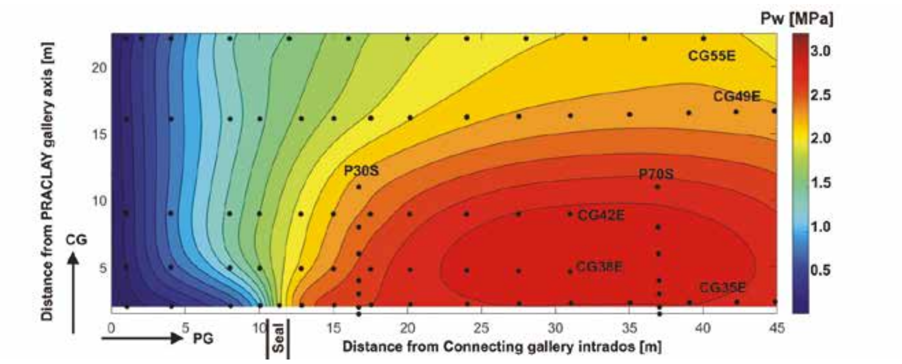


Figure 20 – Pore water distribution in the horizontal plane at the level of the PRACLAY gallery axis prior to the start of heating, plotted by interpolation with five boreholes drilled from the Connecting gallery. The induced drainage by the Connecting gallery can be seen, as well as the effect of pressurisation of the backfilled part of the PRACLAY gallery along CG35E

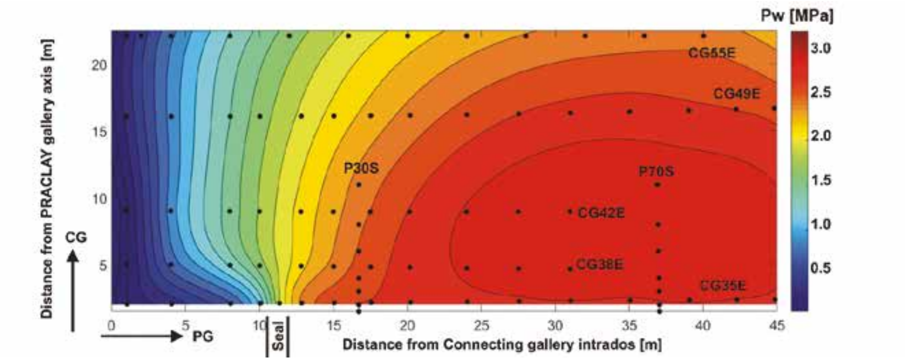
Figure 21(a) to Figure 21(c) show the evolution of the pore water pressure at different moments in time: when the target value of 80°C is reached and after two and five years at 80°C, respectively. It can be seen that the excess pore water pressure develops around the PRACLAY heated section and the maximum excess pore water pressure is located around the middle part of the heated section (at a distance of around 30 m to the Connecting gallery). The hydraulic seal plays its part as a hydraulic cut-off and maintains a high pore water gradient zone around the seal from the heated to the non-heated section. The extent of the hydraulically affected zone increases over time.



21(a) – At 80°C at the interface between the Boom Clay and the concrete lining (August 2015)



21(b) – After two years at 80°C at the interface between the Boom Clay and the concrete lining (August 2017)



21(c) – After five years at 80°C at the interface between the Boom Clay and the concrete lining (August 2020)

Figure 21 – Pore water pressure distribution around the PRACLAY gallery at the start of the stationary phase when 80°C was reached (a), after two years at 80°C (b) and after five years at 80°C (c)

EVOLUTION OF THE HYDRAULIC SEAL

The pore water pressure and total pressure evolution in the instrumented section of the seal were continuously monitored during the heating phase. Figure 22, 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 bentonite ring/Boom Clay interface is well closed and impervious. Moreover, the pore water pressure inside the PRACLAY gallery is maintained at a level of approximately 2.8 MPa as expected due to the good performance of the seal.

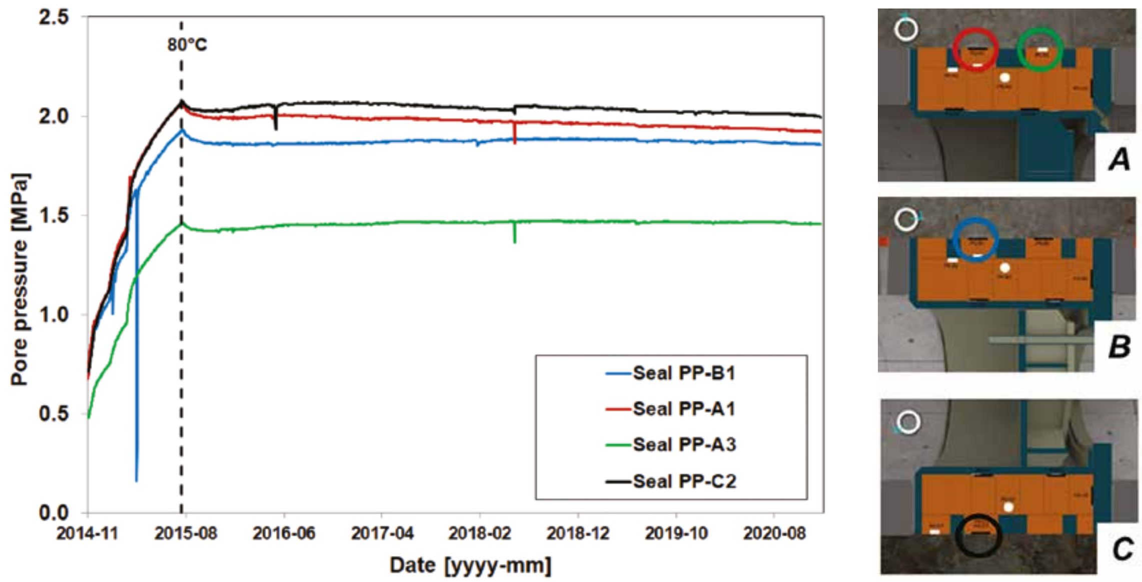


Figure 22 – Evolution of the pore water pressure at the Boom Clay/bentonite interface

In order to highlight the effect of the seal, Figure 23 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 an indication of the good hydraulic cut-off created by the seal.

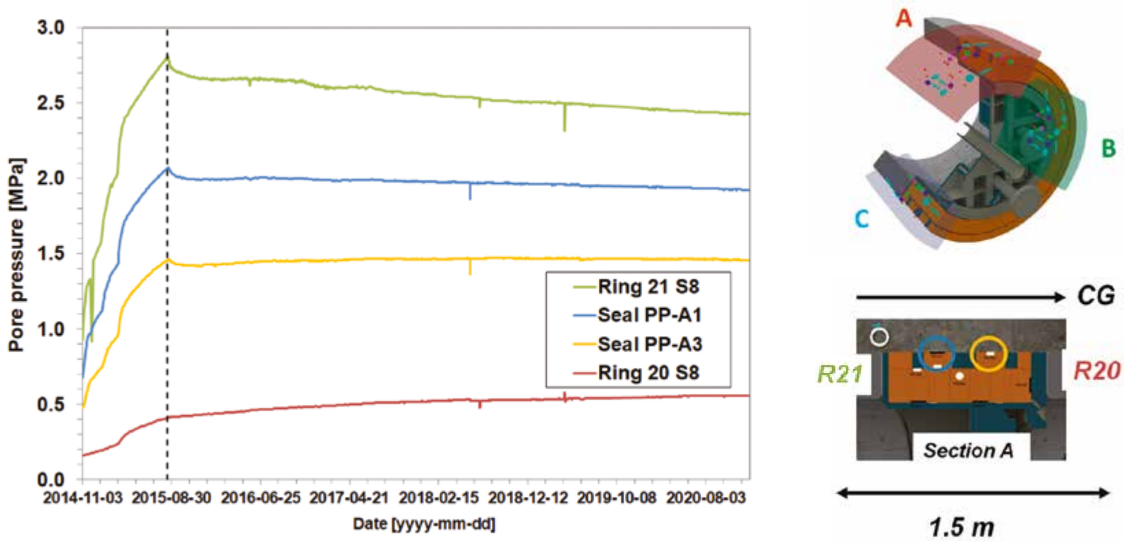


Figure 23 – Pore water pressure evolution at the Boom Clay/concrete lining and Boom Clay/bentonite interfaces

The evolution of the total pressure at the Boom Clay/bentonite interface can be seen in Figure 24. A slow increase is observed during the start-up heating phase. This increase seems to be steady. A variation in total pressure of about 1 MPa has been observed since the switch-on of the heating system. 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.

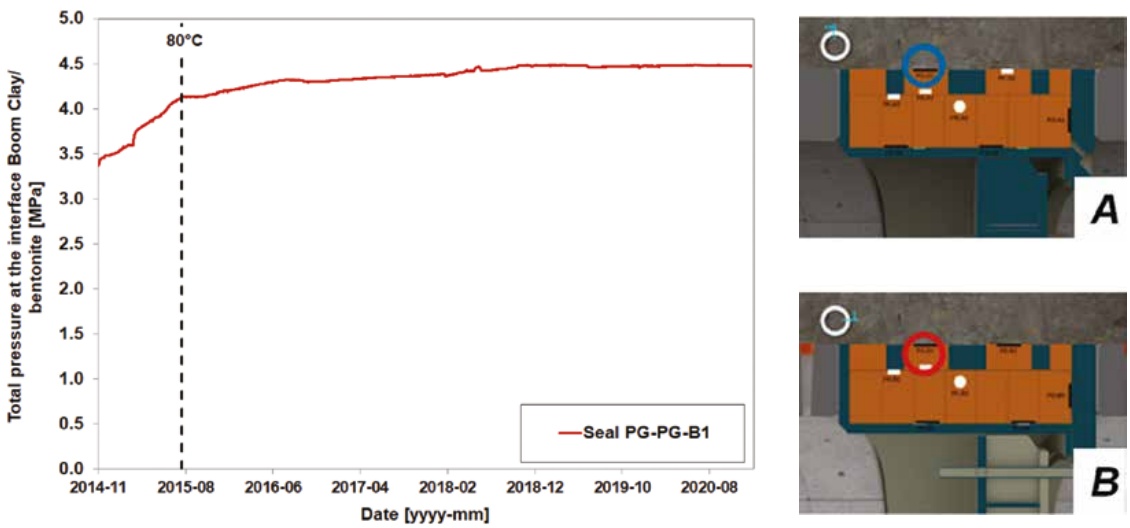


Figure 24 – Total pressure at the Boom Clay/bentonite interface in sections A and B

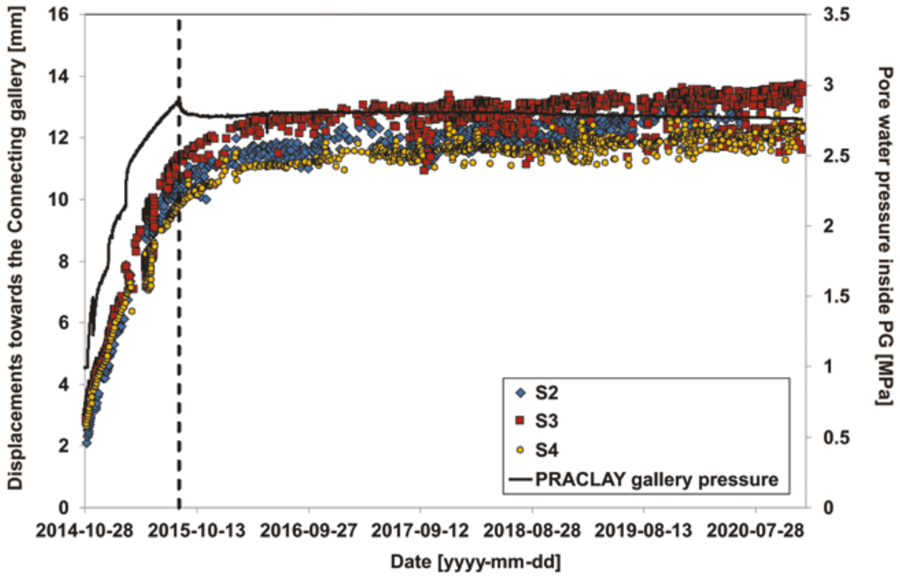


Figure 25 – Evolution of the movement of the seal structure towards the Connecting gallery since the beginning of the heating phase

1.4. Geometry of the PRACLAY experimental set-up

A well-defined and uniform description of the PRACLAY set-up geometry and sensor coordinates is essential for technical follow-up and scientific interpretation. In 2020 extra effort was devoted to reviewing and verifying all existing data to ensure that it had been correctly implemented with sufficient accuracy for the follow-up. In particular, this concerns the coordinates of all sensors and the geometry of the different components used for the numerical interpretation. This data includes survey data from HADES and the instrumentation boreholes, as-built drawings of instrumented casings and other structural components. Based on all this data, the coordinates of the PRACLAY set-up, including the sensors (mainly the borehole filters), have been calculated. The existing information was reviewed and/or validated in 2020.

In addition to the Lambert72 data format, which is the default format for survey data in Belgium, a local coordinate system adapted to the PRACLAY geometry has been defined, in which the coordinates can be more intuitively understood and are more convenient for modelling. This geometry data is then used both internally (follow-up and modelling of the PRACLAY Heater test) and externally, in particular for the EURAD – WP HITEC project, in which the PRACLAY Heater test will be a numerical benchmark exercise. Traceability back to the raw data, such as survey data, as-built drawings and field reports from underground construction work, has been maintained. This action has resulted in well-structured management of all historical survey data relevant to the PRACLAY tests. The local coordinate system, the coordinates of the main components of the PRACLAY set-up and the sensors, and the methodology to calculate them have been reported in detail in a EURIDICE report entitled 'PRACLAY structure and sensor coordinates'.

1.5. THM characterisation of the Boom Clay around the PRACLAY gallery

Constant efforts have been made to improve and support the interpretation of the PRACLAY Heater test, enabling us to improve and confirm the THM characterisation of the Boom Clay. The stepwise improvement in the interpretation of the PRACLAY Heater test is largely based on knowledge gained from the small-scale ATLAS heater tests (ATLAS I, II, III & IV), which were performed between 1993 and 2012 in the HADES URL. Together with the large-scale PRACLAY Heater test, these tests provide data and knowledge to examine the THM responses of the Boom Clay around disposal galleries to heating on different scales. Moreover, the data and knowledge from the heater tests help to confirm and/or refine the THM property values obtained from the laboratory characterisation programme, especially the cross-anisotropic thermal conductivity and mechanical properties of the Boom Clay.

THERMAL CHARACTERISATION BASED ON IMPROVED 3D THERMAL MODELLING OF THE PRACLAY HEATER TEST

Many numerical modelling studies have been carried out to interpret the observed temperature evolution around both the ATLAS heater borehole and the PRACLAY gallery, and to determine whether the measured temperature can be accurately reproduced using a single set of thermal conductivity values $\lambda_{//}/\lambda_{\perp}$ (parallel/perpendicular to the bedding plane) for the Boom Clay.

In the past few years, a refined set of Boom Clay thermal conductivity values, $\lambda_{//}$=1.90 W/(mK) and $\lambda_{\perp}$=1.20 W/(mK), has been obtained by numerically modelling both heater tests.

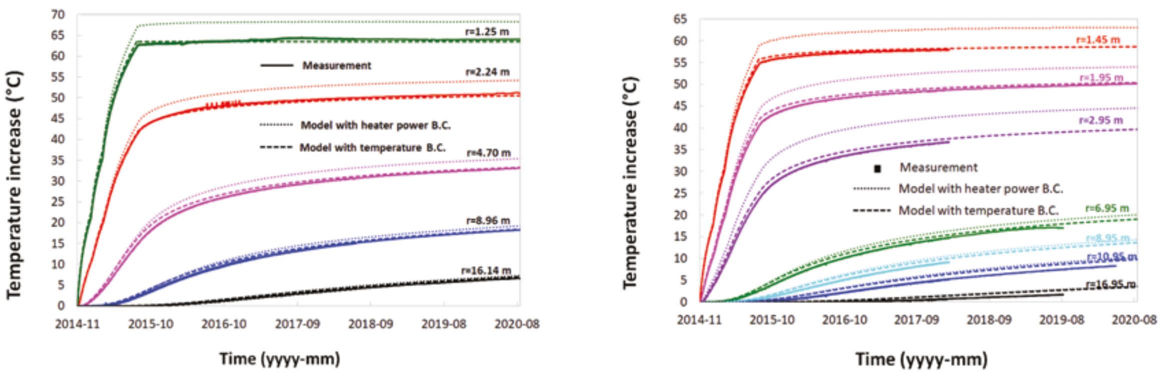
Using this set of thermal conductivity values:

- All temperatures measured in the small-scale ATLAS IV Heater test can be excellently reproduced by a 3D thermal model.
- Temperatures measured in the mid-plane of the large-scale PRACLAY Heater test can also be interpreted with good accuracy by a 2D plane strain thermal model using the temperature at the lining extrados as boundary condition.

However, when using this set of values in a full 3D thermal model for the PRACLAY Heater test with the heater power as boundary condition at the location of the primary heater (3D Model with Heater Power Boundary Condition), the temperatures measured around the PRACLAY gallery are generally overestimated, with a maximum deviation of up to 5°C by modelling after extensive comparison (see Figure 26 and Figure 27).

This overestimation can be linked to uncertainties such as a potential heat loss during transfer of power from the control system to the heated gallery, non-uniform power due to the irregular heater cable structure, and the uncertain amount of heater power transferred to the backfill sand and the lining. In order to overcome the impact of these factors on the temperatures modelled in the Boom Clay by the 3D Model with Heater Power Boundary Condition, the thermal interpretation of the PRACLAY Heater test has been improved by a '3D Model with Temperature Boundary Condition'.

In the 3D Model with Temperature Boundary Condition, the temperature measured at the interface between the lining and the Boom Clay is used as the thermal boundary condition. Consequently, the modelled temperature changes in the Boom Clay depend only on the thermal behaviour of clay. This obviously facilitates the thermal characterisation of the Boom Clay and complies with the intended thermal boundary condition for the PRACLAY Heater test. Using the aforementioned set of Boom Clay thermal conductivity values in the 3D Model with Temperature Boundary Condition, very good agreement is achieved between the modelled temperature and the temperature measured since the switch-on of the heater until the end of first five-year stationary heating phase (see Figure 26 and Figure 27).



(a) Horizontal direction

(b) Vertical direction (due to sensor failure, measurements at some sensors are not complete)

Figure 26 – Temporal evolution of temperature increase at sensors in the mid-plane of the PRACLAY Heater test

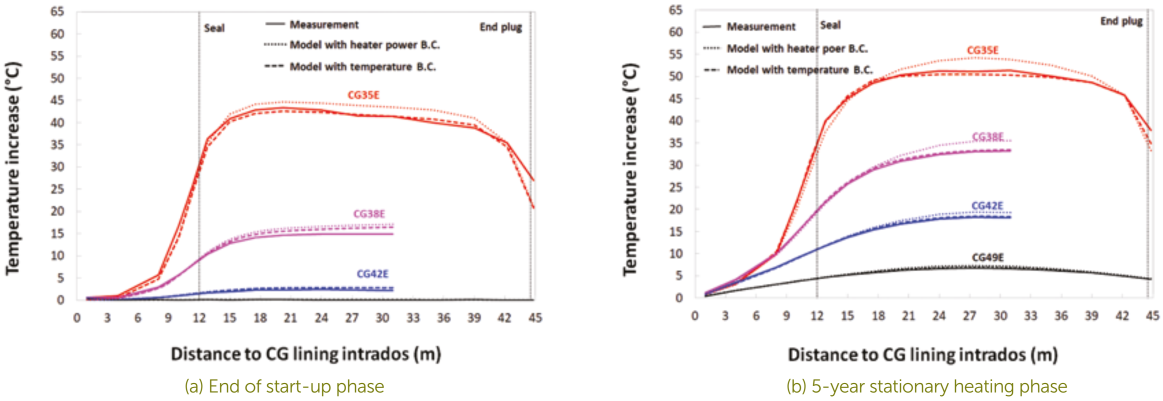


Figure 27 – Temperature increase profiles along four horizontal boreholes parallel to the PRACLAY gallery (i.e. CG35E/CG38E/CG42E/CG49E; see Figure 13 for borehole locations) at two different times

The measured temperature in both the small-scale ATLAS IV Heater test and the large-scale PRACLAY Heater test can therefore be excellently interpreted by modelling using a single set of cross-anisotropic thermal conductivity values for the Boom Clay. This also indicates that the impact of the extent of the THM perturbation on the thermal conductivity of the Boom Clay is not significant.

A paper entitled *Thermal characterisation of the Boom Clay based on numerical interpretation of both a small-scale and a large-scale heater test in HADES URF, Belgium* has been drafted and will be submitted to a peer-reviewed international journal. This paper summarises the thermal interpretation of both the small-scale ATLAS IV and the large-scale PRACLAY heater tests.

IDENTIFICATION OF THE RANGE OF BOOM CLAY THERMAL CONDUCTIVITY VALUES BASED ON INVERSE ANALYSIS OF BOTH ATLAS IV AND PRACLAY HEATER TESTS

Various sets of Boom Clay thermal conductivity values have been estimated on the basis of the thermal interpretation of the ATLAS and PRACLAY heater tests and the most recent relevant laboratory tests. To unify the range of the estimated Boom Clay thermal conductivity values – which will be used for the safety analysis of the repository design – a new study has been defined and launched.

This study aims to identify the range of Boom Clay thermal conductivity values, based on numerically inverse analysis of the measured temperatures from the small-scale ATLAS IV Heater test and the large-scale PRACLAY Heater test, as well as on uncertainty analysis. The sets of thermal conductivity values obtained after independent analyses of the ATLAS IV and PRACLAY heater tests will be compared with each other and with the thermal conductivity values deduced from laboratory tests. These comparisons will enable identification and unification of the Boom Clay thermal conductivity.

The study will be performed step by step as follows:

- Identify the Boom Clay thermal conductivity range based on inverse analysis of the heating phase and early period cooling phase of the ATLAS IV Heater test (ongoing).
- Identify the Boom Clay thermal conductivity range based on inverse analysis of the six-year heating phase of the PRACLAY Heater test.
- Unify the Boom Clay thermal conductivity range by comparing the values obtained from the above two independent analyses with those from the most recent laboratory tests.

CONTINUOUS HYDRAULIC CHARACTERISATION OF THE BOOM CLAY BY MEANS OF IN-SITU PERMEABILITY TESTS

A new in-situ permeability test campaign was carried out in 2020 by conducting tests on 112 filters in the Connecting gallery boreholes around the PRACLAY gallery. The 2020 test campaign is a continuation of the previous test campaigns carried out before April 2018.

The aims of the 2020 test campaign are as follows:

- To complete the database by measuring the Boom Clay hydraulic conductivity and intrinsic permeability on the filters where the permeability tests had never been performed.
- To follow up the evolution of the Boom Clay hydraulic conductivity and intrinsic permeability with time and temperature on the filters where the permeability tests had been performed before.
- To check the impact of the THM perturbation induced by the large-scale PRACLAY tests on the hydraulic conductivity and intrinsic permeability of the Boom Clay.
- To support the scientific interpretation of the PRACLAY Heater test.

A detailed analysis and interpretation of the permeability measurement results from the 2020 test campaign will be carried out next year with reference to the results from the pre-April 2018 test campaigns.

1.6. Reporting on the scientific interpretation of the first years of the PRACLAY Heater test

The large-scale in-situ PRACLAY Heater test has been running for six years. A report entitled *Scientific interpretation of the first years of the PRACLAY Heater test* has been drafted. This report aims to summarise, providing a clear context, the scientific interpretation of the first few years of observations from the PRACLAY Heater test by means of the appropriate numerical THM models, and to present the Boom Clay THM characterisation results based on this interpretation. The report will provide important input for the SFC1 report on the geological disposal of high-level waste programme led by ONDRAF/NIRAS.

1.7. Mid-term evaluation of the PRACLAY Heater test

1. By the end of 2020, the PRACLAY Heater test had been running for more than six years. The observations, together with the numerical investigation, indicate that the whole experimental set-up is working as expected and demonstrate that this experiment has been successful so far: the heating system delivers the correct amount of power needed to run the experiment under well-controlled thermal boundary conditions.
2. The seal structure has remained stable and has demonstrated its ability to sustain high pressure inside the PRACLAY gallery. It fulfils its role as hydraulic cut-off in ensuring quasi-undrained boundary conditions for the Heater test.
3. So far, the segmental concrete lining seems to have remained stable, ensuring stable mechanical support for the PRACLAY gallery and the Heater test. 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.
4. The monitoring programme allows for overall follow-up and control of the experiment, even though a number of sensors have failed (e.g. embedded strain gauges in the concrete lining blocks) or have delivered data with artefacts, thanks to the extensive network of instrumentation and the redundancy of critical sensors. The dedicated effort to analyse the long-term performance of all PRACLAY related sensors is described further (section 3.2).
5. The observations from more than six years of heating have confirmed our knowledge of the THM behaviour of the Boom Clay gained from surface laboratory investigations and smaller-scale in-situ heating experiments. Heating on a large scale has not modified its favourable properties as a natural barrier for a potential high-level waste disposal system in poorly indurated clay.

2. Repository feasibility studies

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 concept for geological disposal of radioactive waste in clay.

Within this context, the recent contribution of EURIDICE covers:
- Lessons learnt on the stability analysis of the Connecting gallery for the repository design;
- thermo-hydro-mechanical analysis of a geological disposal facility for high-level radioactive waste in clay formations.

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. Figure 28 illustrates typical strain evolution in a concrete segment, in ring 30 (R30) near the PRACLAY gallery, which has displayed continuous and slow evolution without any abrupt changes, except during excavation of the PRACLAY gallery. The effect of the start-up phase of the Heater test was marked by a change in slope and a slight increase in the strain rate; the latter tends to stabilise after a few years of heating.

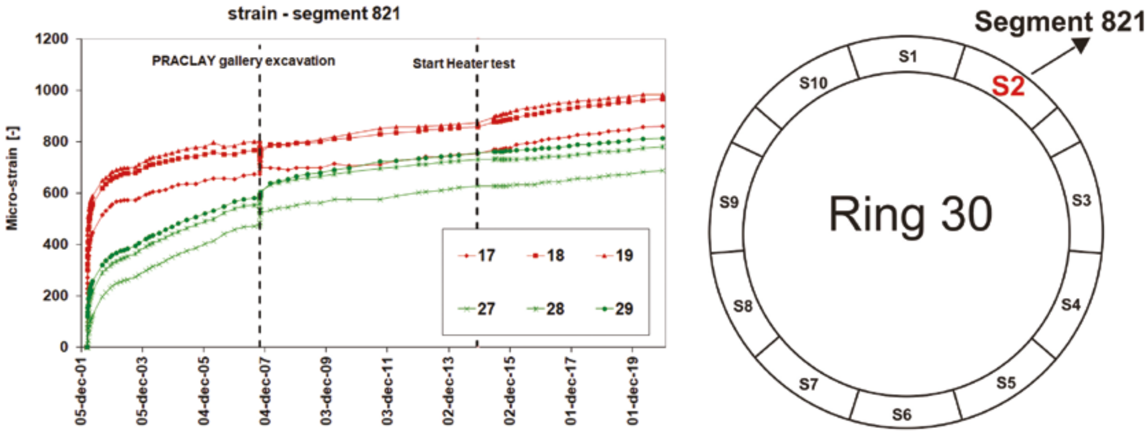


Figure 28 – Typical evolution of the strain in the segmented concrete lining (R30) of the Connecting gallery since the start of the measurements

A few years ago (in 2012), a mechanical analysis of the Connecting gallery was initiated in collaboration with SCK CEN and ENGIE TRACTEBEL. Initially, the goal was to assess the stress state of three instrumented rings based on the strain gauge measurements. After this initial analysis, the scope of the study was extended to include an evaluation of the pressure acting on the lining and a general discussion on the validity of the approach used for the galley design, which is a critical issue for gallery stability and repository gallery design. This study provided valuable information on the state of the Connecting gallery, though some questions remained unanswered, such as the influence of the radial joints on the overall results and the choice of constitutive law for the concrete and the Boom Clay. Moreover, a proper monitoring strategy still has to be defined. From these studies it was possible to conclude that the monitoring data are now embedded in a comprehensive framework, and that there is no imminent stability concern.

As part of a general strategic review of the mechanical analysis of the stability of the Connecting gallery, EURIDICE organised an in-house workshop (SCK CEN, ONDRAF/NIRAS and EURIDICE) in November 2020. The goal was to establish a road map to finally answer the remaining questions and to provide a clear understanding of the mechanical state of the Connecting gallery, which is critical for safe operation of the gallery. More specifically, the lessons learnt of the study on the stability of the Connecting gallery will be important input for the repository design.

The road map will define the actions to be taken and makes a distinction between short-term actions, mid-term actions and long-term actions. The short-term actions comprise continuation of monitoring (strain gauges, topographical survey, visual inspection of the concrete, strength characterisation of the concrete), a new analysis of the stresses inside the concrete segments and re-evaluation of the ground pressure acting on the lining. The mid-term actions include the development of theoretical tools through PhD research (elasto-viscoplasticity of the clay, new constitutive law for the concrete) that can be used in finite element software and applied to the simulation of the Connecting gallery, the PRACLAY gallery and also to a geological disposal facility. The long-term actions require new developments in a long-term perspective and include new research on monitoring aspects such as the determination of the stresses inside the concrete segments, independently from the strain gauge measurements. The final aim of these actions is to consolidate our knowledge with a view to optimising the final industrial design of a geological disposal facility.

2.2. THM analysis of a geological disposal facility for high-level radioactive waste in clay formations

ONDRAF/NIRAS considers the option of geological disposal in poorly indurated clays to be a possible solution for the long-term management of category B (low-level and intermediate-level long-lived waste – LILW-LL) and C waste (high-level waste – HLW – and spent fuel). This option involves using either the Boom Clay or the Ypresian clays as a potential host formation. These clays are present in continuous strata in the north of Belgium down to a depth of 400 m and 600 m for the Boom Clay and the Ypresian clays, respectively. One proposed option for the management of category B and C waste is therefore geological disposal in poorly indurated clays at a depth of between 200 and 600 m.

Within this context and at the request of ONDRAF/NIRAS, EURIDICE has developed a numerical model to simulate the thermo-hydro-mechanical response of the geological disposal facility when heat-emitting C waste (vitrified waste (CSD-V) or spent nuclear fuel assemblies (UOX - 8ft, UOX - 12ft, UOX - 14ft and MOX)) are placed in the disposal galleries. The main goal is to verify whether the clay can be damaged by the heating process, taking into account the present constitutive laws and parameters deduced from the PRACLAY Heater test modelling. The thermo-hydro-mechanical evolution of the near field and far field will be analysed to determine where the clay is more likely to be adversely affected by heat. The outcome of this study provides important input for the repository design, especially for determining the distance between disposal galleries.

The numerical model was developed in 2018-2019 using the finite element software COMSOL Multiphysics® and focused on poorly indurated clays by simulating the effect of heat on the natural barrier system (NBS). Three depths were taken into account, i.e. 200 m, 400 m and 600 m. Five source terms for heat were also considered, corresponding to the five categories of supercontainers: SC-1 (CSD-V or vitrified waste), SC-2 to SC-4 (UOX of different lengths) and SC-5 (MOX).

A dedicated report was delivered at the beginning of 2020. The next step will be to focus on a more detailed analysis of the transferability of the THM parameters of the Boom Clay gained from HADES and surface laboratories to the Boom Clay at different depths and locations, in order to refine the THM analysis of a repository.

3. Instrumentation & Monitoring

Since construction work began on HADES 40 years ago, monitoring has been a key activity. It is an essential aspect of the many field test set-ups and demonstration tests, it played an important role during the construction of HADES and is continuously used for assessing the stability of the HADES infrastructure. As a result, over the past four decades, we have gained considerable expertise in monitoring and the associated instrumentation. The sheer number of sensors already installed require an appropriate system for record-keeping and maintenance. The sensors deployed in HADES also provide us with a wealth of information on their performance in repository-like conditions. This will be very useful in future applications, which could include more advanced demonstration tests, instrumentation of pilot facilities, or actual repository monitoring. The latter is also an important research topic in its own right, as monitoring is considered an essential component in the development of final geological repositories.

3.1. Operational work (inventory, maintenance, calibration, etc.)

Work to streamline the management of the installed sensors and associated instrumentation (such as data acquisition systems) continued in 2020. Steps to draw up a complete and well-organised inventory of the sensors and other measuring equipment have been taken by further implementing the LabTool platform. This fits in with the broader aim of producing a complete scientific and technical inventory of the HADES URL. The process started by defining the hierarchy of the different HADES components. Details from the different instrumentation components are now being entered in LabTool, with priority given to the most relevant set-ups (PRACLAY, ATLAS and the updated MEGAS set-up). The original idea of a complete migration of the measurement data linked to the sensors from the existing 'Daily' data management system has, however, been reviewed. A hybrid system, in which the well-proven functionality of the Daily system is maintained, is now considered the most efficient solution.

As mentioned above, as a result of the installation of many experimental set-ups over the years, the HADES laboratory is equipped with thousands of sensors. Monitoring these sensors results in a huge amount of data, making managing it a big challenge. Most of the sensors are connected to a data acquisition system, which transfers the sensor data to a database. Via Daily (current data management software), all the data in the database can be accessed. However, the goal of Daily does not cover the whole package of data management and a new tool, LabTool, was therefore developed at SCK CEN for this purpose.

LabTool was developed as a Lab Information Management System (LIMS). Applied to HADES, it makes it possible to store all equipment-related information in a hierarchical structure, which enables the user to build a virtual inventory mirroring reality. A screen shot illustrates this structure for the piezometer borehole CG49E in the Connecting gallery (Figure 29).

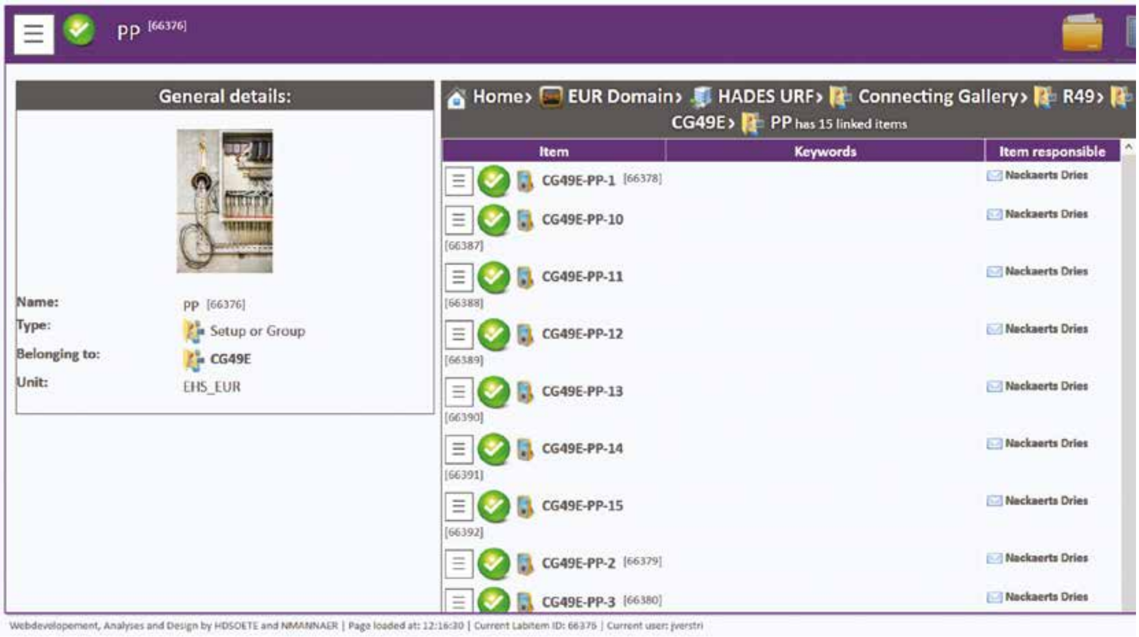


Figure 29 – Screenshot of the LabTool application for managing all instrumentation related data.

In this way, a unique data repository is created to retrieve the information needed. This includes both the sensor data (linked to the database, with enhanced functionalities such as data validation) and all relevant information regarding the equipment (calibration certificates, installation information, manuals, wiring diagrams, etc.). Until now Daily has been used for data consultation and visualisation, but with LabTool this can be expanded to inventory management of the equipment (e.g. data acquisition components) as well. One of the features, for example, is providing reminders of yearly calibration. All the relevant information will also be linked to an item using Alexandria, whose versioning feature makes it easy to retrieve the latest information on the required equipment. This will not only make it easier to find the right information but also enhance the traceability of this information.

All these features will help improve and structure the workflow regarding instrumentation and monitoring in HADES.

As part of the calibration programme, the pressure transmitters in the PRACLAY, ATLAS and MEGAS set-ups were calibrated once again in 2020. For most of the sensors, this process has now evolved into an established yearly operation, which makes it possible to maintain or increase the accuracy of the transmitters. Moreover, the calibration data over several years also gives a more detailed picture of long-term sensor performance. Finally, the calibrations also provide input to review and improve the calibration process itself, from operation to interpretation and application of the results. This experience will also enable us to automate at least part of the calibration process to increase our efficiency.

3.2. 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 long-term sensor performance 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 and concluded in 2018, dealt with the performance assessment of the instrumentation installed as part of the CLIPEX project. Based on this study, a paper entitled *Assessment of instrumentation performance in the context of geological radwaste disposal – a first case study in the Belgian URL HADES* has been written, and will be submitted to a journal in 2021.

The second study began in 2018 and is looking at the PRACLAY in-situ experimental set-up. It follows the same methodology as that developed for the experimental set-up of the CLIPEX project: 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.

The first parts of this study were already started in 2018: detailing the assessment methodology and the scope, outlining the historical context, and producing a detailed description of the monitoring set-up. The 1300+ sensors were grouped into more than 33 'sensor sets', each containing similar sensors (same technology) installed in similar conditions.

Assessment involves checking each individual sensor against a number of indicators. The five main indicator categories that were defined for the first study (assessment of the CLIPEX project) have been applied again. The table below details these categories.

CATEGORY	INDICATORS
Installation	Date of installation, available procedures, issues during installation
Sensor operation	Data acquisition, operational / functionality
Environment	Host medium of sensor, presence of conditions that can have an effect (pressurised water, high temperatures, gas injection, radiation, etc.)
Measurement quality	Signal quality (noise, outliers, etc.), representativeness of measure-ment, influence of environmental factors
Sensor characteristics	Sensitivity, accuracy, calibration results and drift (where available)

The indicator results are summarised in spreadsheet tables (one for each sensor set). The corresponding assessment section of the report contains the contextual information on these indicator results, additional analyses depending on the sensor type and the available data, and conclusions on the performance in the PRACLAY set-up, together with the potential of the sensor technology for future applications.

The first draft was discussed with ONDRAF/NIRAS in 2019. It was concluded that, in view of the vast number of sensors, more relevant information could be obtained from the data gathered, for example using statistical methods, to investigate in further detail aspects such as life expectancy of the sensors, related to the experimental phases and the related changing environmental conditions, such as temperature and water pressure evolution. As work in 2019 was delayed due to other tasks (mainly the final activities relating to the Modern2020 project) and the departure of a key employee, it could not be completed that year, and was resumed only this year. The aim is to produce an extensive report to be delivered to ONDRAF/NIRAS in 2021. Starting from an assessment of the more than 1300 sensors according to the indicators mentioned, this report discusses the representativeness and added value of the measurements in the context of PRACLAY. From this, the lessons learnt for design and operation of monitoring systems for future large-scale setups, demonstration tests, pilot facilities (and ultimately for repositories) will be described.

4. Core management and GSIS

EIG EURIDICE coordinates the management of the ONDRAF/NIRAS drill cores. This includes packaging cores to ensure good conservation during storage, drawing up an inventory of the cores from both HADES 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 30).

Figure 30 – Storage of packaged drill cores at EIG EURIDICE

EIG EURIDICE is also responsible for the further development and support of the GSIS database (GeoScientific Information System). This is an integrated database that centralises all data concerning drilling, drill 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.

In 2020 only few activities were performed for GSIS because priority was given to the surface disposal programme for category A waste. The core management workflow was further implemented in GSIS. GSIS support for core management includes the complete workflow to track all information about a specific core, from core request to every operation that is applied to a core during the sampling process. For this, object-tracking metadata records are made for each core. This metadata can be used for the pre-selection of samples requested for research. The metadata records can be supplemented with links to the scientific outcome of research on these cores.

On the EURIDICE website, a dedicated page has been added concerning the procedure for requesting Boom Clay samples (Figure 31). Applicants can find further details about the formal procedure and the conditions governing the use of Boom Clay samples from the Belgian radioactive waste management programme for their own research. This formal procedure has been developed by EIG EURIDICE, together with ONDRAF/NIRAS and SCK CEN, in order to ensure traceability and quality standards in assigning geological samples for research purposes. The procedure covers the entire process from sample request through to publication of the results and makes use of just one form divided into several sections.

Figure 31 – Dedicated web page for requesting Boom Clay samples

5. International activities

5.1. Research projects

INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA) - COMPENDIUM OF RESULTS OF RD&D ACTIVITIES CARRIED OUT AT UNDERGROUND RESEARCH FACILITIES FOR GEOLOGICAL DISPOSAL

A *Compendium of Results of RD&D Activities 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 conducted in underground research facilities over the past 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 to more in-depth information and reports on URF RD&D results. The objective of this document is to provide a list of the existing URFs around the world, together with a comprehensive overview of the main information on RD&D results obtained from them to date. This information will be presented together with details 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 2019 the IAEA invited EIG EURIDICE to take part in two 'Consultancy Meetings on the Compendium of Results of RD&D Activities carried out at Underground Research Facilities (URFs) for Geological Disposal'. EURIDICE's scientific coordinator, Xiang Ling Li, attended both of these and is coordinating the Belgian contribution to this Compendium.

With a significant contribution from SCK CEN's W&D expert group, a final report on the *Investigations, experiments and demonstrations carried out in Belgian URF HADES* was delivered to the IAEA in 2020. The report covers the following aspects:

- A general description of the HADES URL.
- Former roles played by the HADES URL and future goals.
- Design of the HADES URL.
- Key phases of HADES URL development.
- Research, experiments and demonstration activities:
  For each of the 30+ activities/experiments included in the report, the background, main and specific objectives, experimental approaches, key findings and lessons learned are described. A list of references for each experiment has also been provided. Some of the experiments have been selected for inclusion in the main report of the IAEA's Compendium.

The IAEA's objective is to publish the Compendium in 2021.

With its contribution to this compendium, EIG EURIDICE increases the international scientific visibility of the RD&D carried out in the HADES URL within the Belgian national programme for geological disposal. Active presence in the different IAEA platforms such as the URL network and consultancy for the compendium of the RD&D activities in URFs provide opportunities for EURIDICE to present its RD&D activities in HADES, to exchange RD&D challenges and to join the training program organised by IAEA.

At the national level, the work for the compendium has an added value for EURIDICE's knowledge management as it is a useful and efficient tool to structure the technical/scientific knowledge and expertise.

EUROPEAN JOINT PROGRAMME ON RADIOACTIVE WASTE MANAGEMENT AND DISPOSAL – EURAD

As part of the European Joint Programme on Radioactive Waste Management and Disposal (EURAD), the first wave of projects, or 'Work Packages' (WPs), started on 1 June 2019. EURIDICE is involved directly as a linked third party of ONDRAF/NIRAS in the WP HITEC – Influence of temperature on clay-based material behaviour. EURIDICE is also involved indirectly in the WP GAS – Mechanistic understanding of gas transport in clay materials by providing scientific and technical support to SCK CEN's W&D expert group, which is a partner of the WP GAS.

In the course of 2020, EURAD launched the second wave of the call for projects. EURIDICE, jointly with SCK CEN, responded to the call regarding two new projects (Work Packages): MODAT (Monitoring Equipment and Data Treatment for Safe Repository Operation and Staged Closure) and MAGIC (chemo-Mechanical AGIng of Cementitious materials under coupled disturbances based on a multiscale approach). These two projects will start in 2021 if accepted by EURAD.

WP HITEC - Influence of temperature on clay-based material behaviour

In WP HITEC, EURIDICE contributes mainly to Tasks 1 and 2, dealing with the clay host rock:

- Task 1.2: State-of-the-art reporting on the THM behaviour of clay host rocks
- Task 2.3: THM modelling of the effect of temperature in the near and far field – Benchmark exercise

The kick-off meeting of WP HITEC was organised on 27 June 2019 in Paris, during which EURIDICE presented its work schedule for the different Tasks and Sub-Tasks in which it is involved.

For Task 1.2, the state-of-the-art report was delivered in 2019 and reviewed by the work package expert in 2020.

Task 2.3 mainly consists in a benchmark exercise on the numerical modelling of several in-situ heater tests running in different URLs (Mont Terri, Bure and HADES). The experimental data of the large-scale in-situ PRACLAY Heater test in HADES will be used as one of the data-sets for this exercise. EURIDICE provided support in defining the benchmark exercise by increasing the complexity in a stepwise way. This stepwise approach of the benchmark exercise was presented during the general progress meeting in June 2020. The initial results are scheduled to be delivered in January 2021. In parallel, EURIDICE is also working on this benchmark with the objective of establishing innovative tools within the numerical codes that we are using, such as contact elements. These tools allow a better simulation of the THM behaviour at the contact zone between different components (such as the contact between the lining and the Boom Clay). By supporting this benchmark exercise, EIG EURIDICE gets the opportunity to share in-situ experimental results, to work with international colleagues, to exchange the challenges faced with numerical modelling of such a large-scale and long-term in-situ experiment and thus to provide new insights on the THM process of the host rock.

WP GAS – Mechanistic understanding of gas transport in clay materials
ONDRAF/NIRAS wishes to determine the parameters associated with gas diffusion in the Boom Clay. In addition to the laboratory experimental programme, an in-situ experiment has been planned as part of WP GAS to confirm and/or improve current knowledge of diffusion of dissolved gases in the Boom Clay on a larger scale. Based on the screening in HADES to assess the possibility of re-using existing experimental set-ups, MEGAS has been chosen for the in-situ gas diffusion experiment. The SCK CEN's W&D expert group is managing the test (currently in the preparatory phase), with EURIDICE providing the necessary technical and scientific support.

EURIDICE has been supporting the W&D expert group with the following activities:
- Characterising the hydraulic conductivity of the Boom Clay surrounding the injection and monitoring filters of the gas diffusion test set-up.
- Moving the test set-up for the gas diffusion test to the HADES URL, and connecting the set-up to the MEGAS tubing system and DAQ system.
- Giving advice on piping and instrumentation of the experimental set-up and the additional sensors to measure flow rate and water level inside the vessels.

5.2. Education and training

Within the context of EURAD, a training course entitled 'Multiphysical couplings in geomechanics: a focus on thermal effect and gas transfer impact on the behaviour of geomaterials' was organised in January 2020. This related to two EURAD work packages (WPs), WP GAS and WP HITEC, in which geomechanics plays a significant role in understanding the relevant thermo-hydro-mechanical couplings taking place around a disposal gallery. The objective of the course was therefore to provide state-of-the-art knowledge on basic concepts relating to the thermo-hydro-mechanical (multi-physical) couplings: the physical impact of thermal loading and the mechanistic understanding of gas migration. During the training course, EURIDICE delivered a lecture on 'In-situ THM testing at high temperature: poorly indurated clays (Boom Clay)'.

The Deliverable 6.3 ('Training materials of the 1st GAS/HITEC Joint training course') of WP GAS gives an overview of this training course where 70 participants were registered. As written in the deliverable, positive feedback from the participants was given:

> 'The feedback showed that the participants appreciated the content of the school and especially the fact that the lecturers provided a critical view of the current state-of-the-art on the multiphysical couplings in geomechanics. The program of the school was well foreseen, even if modelling lectures were delivered before the presentation of the in-situ experiment, and in hindsight they may have been of more value afterwards. In terms of improvement for the next school, some participants indicated that they would have further benefited if they could have observed the equipment used in the laboratory and in-situ. Combining the next doctoral school with a visit to a laboratory in a research centre and an Underground Research Laboratory should be considered.'
>
> From Collin F., Charlier R. (2020): Training materials of the 1st GAS/HITEC joint training course. Final version as of 24.02.2020 of deliverable D6.3 of the HORIZON 2020 project EURAD. EC Grant agreement no: 847593

6. PhD programme

In 1992, SCK CEN embarked on a programme to support PhD candidates and post-doctoral researchers in a conscious desire to increase its pool of highly specialized researchers and to strengthen its links with universities. SCK CEN works together with numerous universities, both in Belgium and abroad, offering new PhD subjects each year that fit within its own research programmes. To promote research into radioactive waste and disposal issues, SCK CEN and NIRAS/ONDRAF together support PhD theses in this domain.

Within the frame of the SCK CEN PhD programme, and the joint SCK CEN and NIRAS/ONDRAF PhD programme, 3 PhD projects are currently on-going in collaboration with EIG EURIDICE. They are all related to EURIDICE's main research activities on thermo-hydro-mechanical-chemical (THMC) characterisation of the Boom Clay and the engineered barriers.

- In 2016 the 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 funded by SCK CEN and is being pursued in collaboration with Antwerp University.
- In 2017 the project entitled *Investigation of the long-term behaviour of Boom Clay*, was submitted and approved. It is co-funded by ONDRAF/NIRAS and SCK CEN and is a joint collaboration with Laboratoire Navier/CERMES, l'École des Ponts ParisTech. This project was awarded to May Awarkeh, who started working on it in October 2018.
- In 2019 a third project, entitled *Reduced Order Modelling Technique for Coupled Geomechanics Problems*, was approved by SCK CEN's Academy. This PhD research project was initiated at the Université libre de Bruxelles (ULB) and the Universitat Politècnica de Catalunya (BarcelonaTech, UPC) in autumn 2017, independent of the PhD programme at SCK CEN. It was funded through a European Erasmus Mundus Joint Doctorate Programme for the first three years (i.e. autumn 2017 to autumn 2020), and will be funded by SCK CEN for the final year (i.e. autumn 2020 to autumn 2021). This project was awarded to Ygee Larion.

6.1. A Multiscale Approach to Model Early Age Thermo-Hydro-Mechanical Behaviour of non-reinforced Concrete

This PhD research project is in its final stages (due for completion in January 2021). The last year was mainly devoted to finalising the development of a multiscale thermo-hydro-mechanical (THM) numerical modelling framework (Figure 32). This framework relies on crucial material properties, which are determined from the methodology developed as part of this PhD project, including:

- A multiscale pore network model to estimate the water sorption isotherm of cementitious materials and their saturated and unsaturated permeability.
- A multi-mechanism analytical framework developed to estimate the drying shrinkage behaviour of cementitious materials.
- A micromechanical modelling framework that computes the thermo-mechanical properties of cementitious materials, e.g. thermal expansion coefficient and E-modulus, directly from the cement composition and hydration reaction.

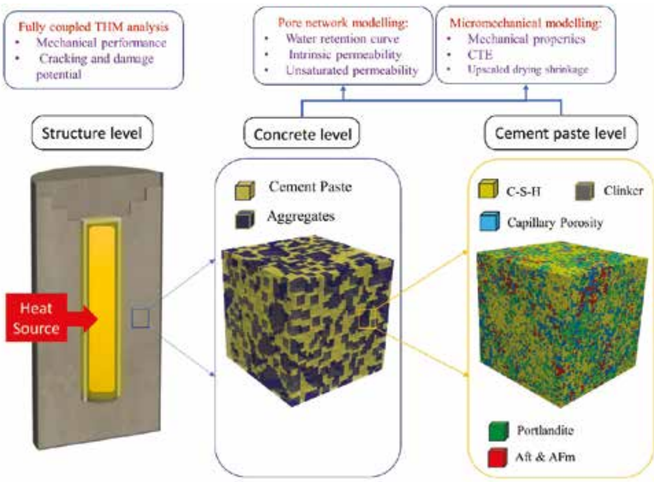


Figure 32 – The multiscale modelling framework developed and output at different scales

The following milestones were reached in 2020:

- Publication of two papers in *Cement and Concrete Composites*, a high-impact peer-reviewed journal: one on a multiscale framework to estimate water sorption isotherms for OPC-based materials (published in 2020) and the other on an analytical framework for estimating drying shrinkage strain of OPC-based hardened cement paste (available online at the end of 2020, to be published in 2021).
- A six-month research visit to Professor Farid Benboudjema's lab (LMT Cachan Paris), during which time the micromechanical framework and large-scale THM modelling were developed under his supervision. Due to the COVID-19 pandemic, the visit was replaced by a series of regular virtual meetings.
- An extensive study on continuum scale modelling of the coupled thermo-hydro-mechanical behaviour of a concrete engineered barrier is under way using the framework depicted in Figure 32; the results will be reported in the PhD thesis, followed by publication in a scientific journal.

6.2. Investigation of the long-term hydro-mechanical behaviour of the Boom Clay

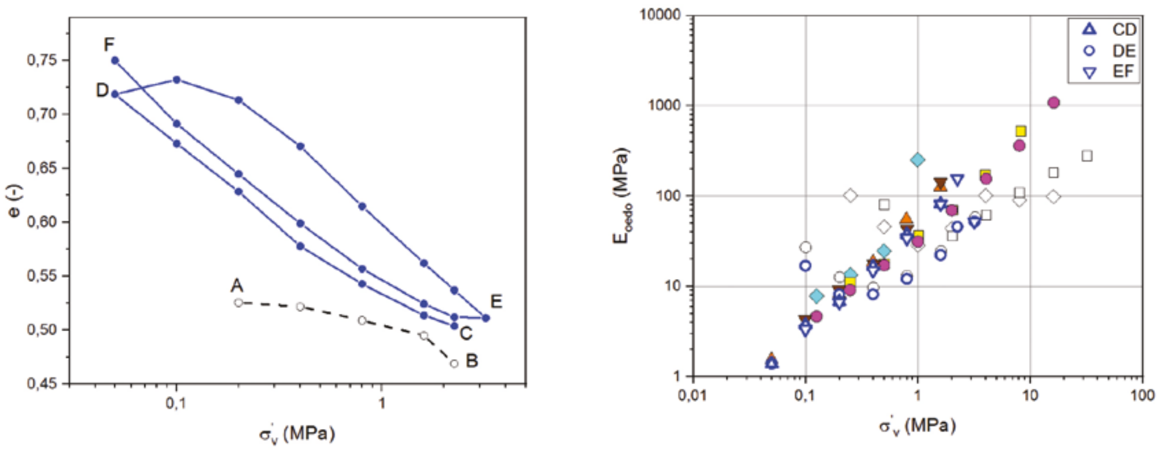
A PhD entitled *Investigation of the long-term behaviour of Boom Clay* was initiated by EURIDICE, SCK CEN's W&D expert group and ONDRAF/NIRAS, and started in October 2018. The reason for pursuing this PhD stemmed from the fact that many studies have been undertaken to understand the long-term behaviour of the Boom Clay, but there are still some knowledge gaps that need to be investigated further, such as gallery convergence during construction and long-term interface behaviour between the Boom Clay and the galleries. These phenomena are very important for the operational phase of disposal, when the repository galleries may be open for a few decades before emplacement of the supercontainers and backfilling of the galleries.

The main objectives of this PhD thesis are:

1. to improve our understanding of the long-term behaviour of the Boom Clay
   a. by conducting a thorough literature review
   b. by developing a new experimental programme, including both laboratory and in-situ tests in HADES
2. to develop a relevant constitutive law taking the long-term behaviour of the Boom Clay into account.

This established methodology is based on oedometric and triaxial laboratory tests, as well as an in-situ dilatometer test that will be set up in the HADES URL. An elasto-viscoplastic constitutive law based on existing results and new experimental results will then be implemented in the numerical software COMSOL MULTIPHYSICS. This will enable us to analyse the results of the in-situ tests and validate the numerical calculations. For this research, Boom Clay cores, vacuum-packed in Al-coated PE foil, have been sent to the CERMES (ENPC) laboratory. These clay cores were taken from HADES from damaged and undamaged areas in a horizontal borehole.

Based on an extensive literature review, a new experimental laboratory programme has been established to study the long-term behaviour of the Boom Clay by means of oedometric and triaxial tests, followed by a microstructural study of samples before and after the tests using mercury intrusion porosimetry (MIP). Oedometric multi-stage loading and unloading creep tests at low (0.05 - 3.2 MPa) and high (0.125 - 32 MPa) pressures have been initiated. These tests begin with manual sample preparation, followed by preparation of the oedometric cell and saturation of samples under the application of in-situ stress to minimise changes in microstructure. These different cycles of loading and unloading make it possible to determine the compressibility curves, the consolidation curves and consequently to identify many parameters of the Boom Clay and the dependent factors for their evolution. As an example, Figure 33(a) presents the experimental oedometric compression curve obtained on a Boom Clay sample during a loading-unloading cycle, and Figure 33(b) shows the oedometer modulus as a function of the applied stresses.



(a) (b)

Figure 33 – (a) Compression curve from low pressure oedometer creep test. (b) Oedometer modulus versus vertical effective stress

The second type of test is oedometric testing at different constant rates of strain. These tests are carried out by placing the oedometric cells in controlled strain presses. In order not to generate high pore water pressure inside the sample, a range of strain rates is determined. At the end of the tests, a correction according to a linear or non-linear solution is necessary for processing the results. Changing the strain rate from one test to another provides the effect of this rate on compressibility curves and its relation to the pre-consolidation pressure. Furthermore, the normalisation of the different compressibility curves as a function of the applied strain rate results in a remarkable comparison between tests at different constant rates of strain and oedometric creep tests at several stages.

In addition, the shear behaviour of the Boom Clay was studied by means of triaxial tests under different experimental conditions. According to the literature, a triaxial creep test under a confining pressure of 2.5 MPa has been performed. It is therefore necessary to complete the work of the literature by carrying out new triaxial creep tests under two different confining pressures of 1 MPa (weak) and 4.5 MPa (strong), and under different constant deviatoric stress levels ranging from 20 to 40 to 60 then 80% of the maximum strength until breakage. This allows the three phases of primary, secondary and tertiary creep of the Boom Clay to be examined. Moreover, this loading under various levels of deviatoric stresses makes it possible to determine the creep threshold below which there is no creep strain generation.

6.3. Reduced Order Modelling Technique for Coupled Geomechanics Problems

When numerically modelling complex THM coupling problems in soils, challenges such as high dimensionality and a long calculation time have to be tackled, especially when repeated calculations are required. The Reduced Order Model (ROM) is a simplified and high-fidelity model that preserves both the essential behaviour and the dominant effects inherent to the problem, but significantly reduces the computational cost. ROM has been widely used in aerodynamics, network systems, fluid dynamics, etc., but its application in the coupled THM problem is rare.

The in-situ ATLAS and PRACLAY heater tests performed in the HADES URL deal with complex THM coupling problems, and their inverse analysis based on finite element method (FEM) modelling is quite time-consuming, or even not feasible in some cases. The ROM technique enables us to perform inverse modelling for parameter estimation as well as uncertainty analysis at a significantly reduced and acceptable computational cost. This is why the W&D and EURIDICE expert groups are involved in this project, with financial support from SCK CEN for the final year (2020-2021) of this PhD thesis.

The PhD student, Ygee Larion, developed a certified ROM technique for transient coupled thermo-hydro-mechanical parametric problems with goal-oriented error estimation in the first two years of his PhD research.

He then applied this ROM technique in both the 3D thermal modelling and 3D THM modelling of the small-scale in-situ ATLAS III Heater test in HADES by working closely with EURIDICE. Compared with FEM calculation, ROM calculation drastically reduced the spatial degrees of freedom of the coupled system by three orders of magnitude. As a consequence, it reduced the computational time significantly by one to two orders of magnitude. Remarkably, there is excellent agreement between the FEM and ROM calculation results. Benefiting from the significantly cheaper ROM solution, full-scale inverse 3D analysis for the ATLAS III Heater test, which requires tens of thousands of repeated calculations, has been performed very efficiently with an acceptable calculation time.

In the final year of his PhD research (2020-2021), Ygee has been drafting a paper for submission to an international journal about the application of ROM in the ATLAS III Heater test and has been developing ROM for the PRACLAY Heater test, taking into account the elastoplastic behaviour of the Boom Clay.

RD&D Part 2
The surface disposal programme for category A waste – cAt Project

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, 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 is 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. This revised version was submitted to FANC in February 2019, culminating in a positive preliminary assessment by the Scientific Council in October 2019. In this assessment, further studies were identified that are to be undertaken before a licence can be granted.

EIG EURIDICE supports the cAt project in the following areas:
- Calculations of the long-term radiological impact and performance of the planned disposal facility.
- Development and validation tests of the hydrogeological models used in the licence application for the planned disposal facility.
- Preparation and instrumentation of the planned test cover.
- Instrumentation of the demonstration test for construction of concrete modules.

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

In 2020 EIG EURIDICE's support was again sought in carrying out additional long-term studies, with particular attention devoted to assessing the containment performance of the disposal system.
Overall, the containment performance analysis serves three purposes:
1. quantifying the expected containment performance of the disposal system as a whole, and that of its constituting systems, structures and components (SSCs) or safety functions;
2. demonstrating that the disposal system and its SSCs/safety functions display robustness against reasonably foreseeable perturbations (e.g. earthquakes, cover erosion,...);
3. demonstrating that the containment performance of the disposal system is commensurate to the hazards associated with the waste.

The latter two objectives partly contribute to the argumentation of the disposal system's level of defence in depth.

To this end, representative system models are developed and implemented from which performance indicators are calculated which help developing the system understanding and assessing the effectiveness of particular SSCs, especially those fulfilling a main role in the long-term safety concept. Three types of performance indicators are considered: 1) indicators describing the evolution of the activity/radiotoxicity in the disposal system (such as the total activity/radiotoxicity present in specific SSCs over time), 2) indicators addressing the transfer of activity (in particular fluxes between SSCs and out of the system) and 3) indicators directly addressing the contribution of individual components.

In the reporting of results, these indicators are complemented with (semi-quantitative or qualitative) indicators and arguments. These are based on understanding and analysis of the processes and characteristics from which the (target) performance of (the components of) the disposal system is derived. For instance, a low hydraulic conductivity of concrete components is imposed as a design requirement, as it is directly correlated to the limitation of water flow in the matrix of these components, constituting a key safety function (in a non-fractured system).

The primary focus in 2020 was on justifying and underpinning the adequacy of the near field models used for assessing the expected performance, building on scientific underpinning and supporting calculations.

Further, the performance analysis results, substantiating the three aims mentioned above, were documented. This documentation is the basis for documenting the outcomes of the performance analysis and substantiating the defence in depth argumentation in chapters 14 and 2 of the safety report, respectively – which is foreseen in 2021. Following approval by the safety authority, the underlying documentation developed will constitute a supporting document to the safety report.

2. Hydrogeological models

A transient site model has been developed in order to support the outcomes of the former Local model, which was designed as a steady-state model. In order to implement the detailed data required in space and time, the recharge input data was first calculated at three scales: dependent on the soil-land use combination, on the basis of monthly time-series, and on the groundwater depth. Boundary conditions and source and sink data were adapted to cope with the model refinements. The hydraulic conductivity values have been updated with the 2019 pump test results. The site model consists of coupled parent and child models, whereby the latter is more finely discretised (Figure 34).

The calibration strategy is based on the flux observations (dilution tests) and on the monthly measured groundwater heads, for the period 2016-2017. The calibration is performed both manually and using a general optimisation method (Monte Carlo Markov Chain analysis). The latter turned out to be very time-consuming, taking weeks of calculation time for the 30,000-50,000 iterations required.

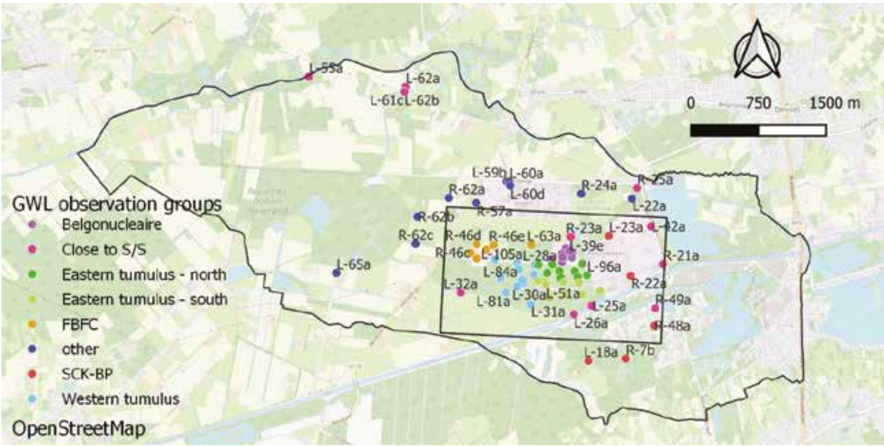


Figure 34 – Contours of the parent and child model, and the groundwater level observation points used for calibration and validation of the model

The validation is performed for a 19-year period (2001-2019) and evaluated by calculating the root mean squared error. Validation is performed using the groundwater heads and flux measurements; e.g. groundwater head observations in selected piezometer are compared to the results of the model. In general, the simulated groundwater levels reproduce the observed ones, although they have the general tendency to underestimate the groundwater dynamics (Figure 35).

Another way to validate the modelled heads is to compare them to the interpolated hydraulic heads from the piezometric measurements. These maps are based on observed piezometric time series filled up between the actual measurement times using a calibrated input-response model and daily rainfall and temperature series. Daily maps for the period 2016 - 2019 were used, the interpolated values were transformed to season and month averages. The same operations were done on the simulated heads using the manually and MCMC calibrated parameters (MCMC results in Figure 36).

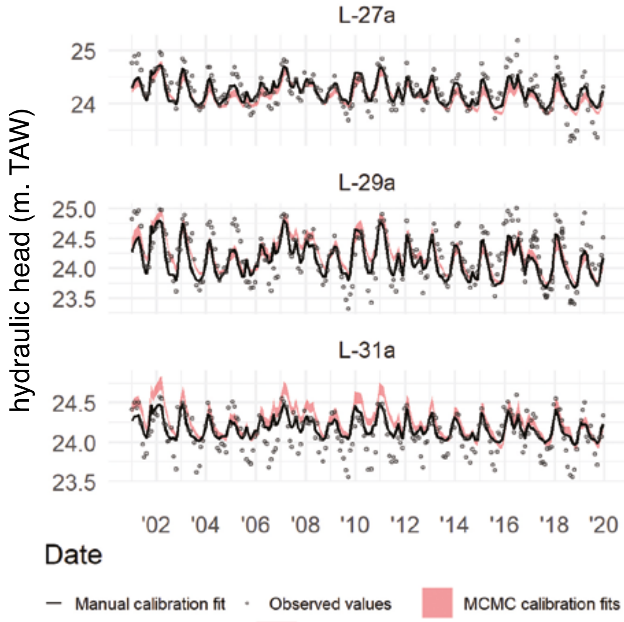


Figure 35 – Comparison between the observed hydraulic heads and the simulated equivalents using parameters calibrated manually and using MCMC

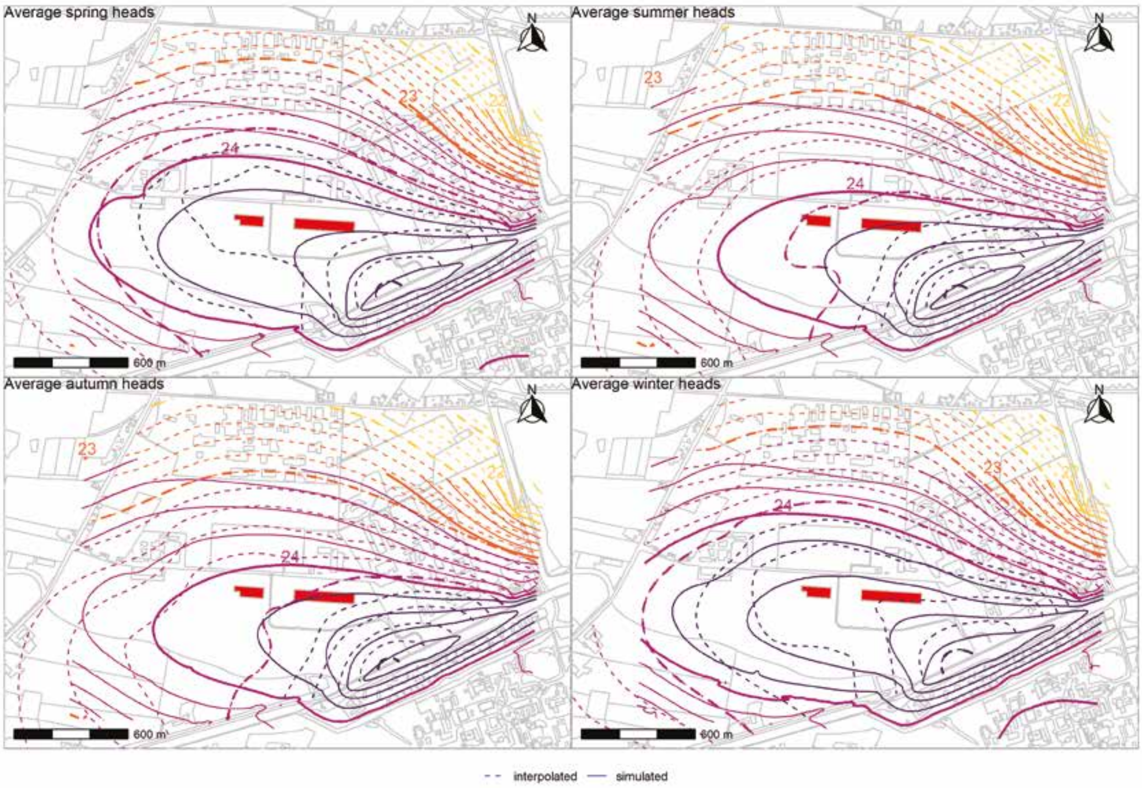


Figure 36 – Comparison between the seasonally averaged MCMC (highest log-likelihood parameter set) calibrated heads and the corresponding seasonally averaged interpolated groundwater level maps

The seasonally averaged heads compare relatively well for the winter season, the autumn heads are mostly overestimated by the model. The heads during the summer season seem to be slightly overestimated by the MCMC calibration. During spring, heads are fitting quite well.

The next steps are processing the geo-transfer factor for the eastern and western tumulus under current and future climate conditions.

3. Test cover

As construction of the test cover has been postponed, little or no work was done on this project. Preparation (licensing and public procurement) will resume in 2021 in order to start on the construction phase of the test cover in 2022.

4. Demonstration test

In order to assess the technical feasibility of the module construction techniques and the industrial feasibility of the concrete that has been optimised for long-term safety and has been tested on a laboratory scale, a demonstration module construction test for the cAt project has been underway since 2011 (Figure 37).

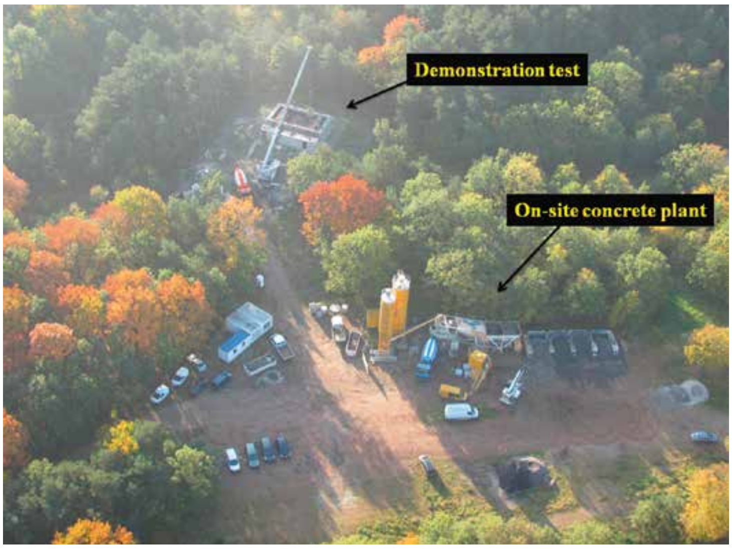
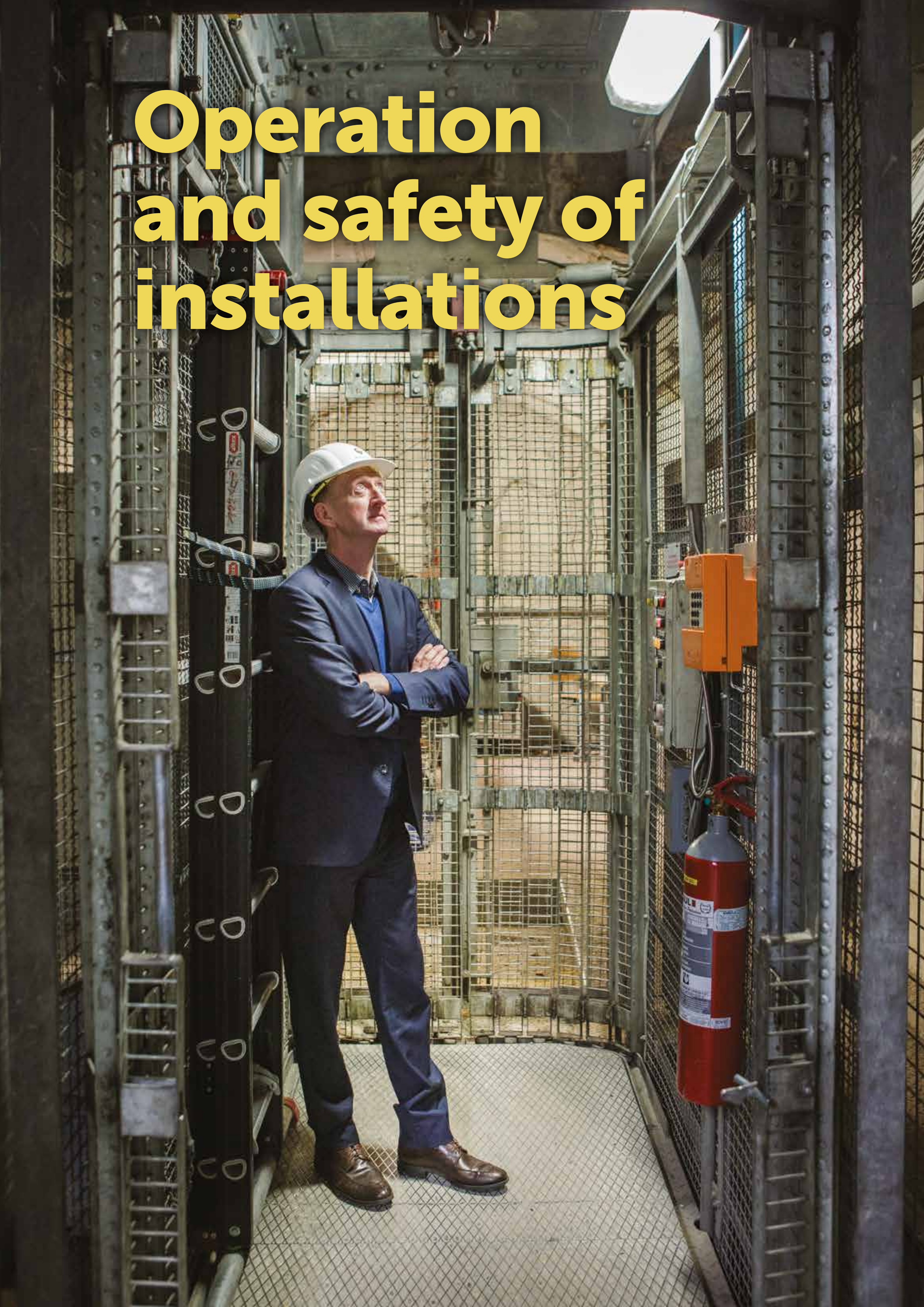


Figure 37 – Overview of the demonstration test

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 2020. Some data collection and analysis continued, however.

Operation and safety of installations



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. The work is performed under several licences.

The **operating licence** is valid until 2024. Due to important changes to the infrastructure (refurbishment of shaft 1), a new operating licence will be required. The application was prepared with the Federal Public Service for Employment, Labour and Social Dialogue and with the community of Mol. The licence application was submitted to the community of Mol at the end of 2020.

The **nuclear licence** of EIG EURIDICE (issued in July 2017) remains valid until the end of 2021.

The current **environmental licence** of EIG EURIDICE was granted on 8 August 2019 and is valid until 30 October 2033.

The primary task of the Operations and Safety team is to maintain the HADES URL and its above-ground facilities, in order to keep the URL operational and available for researchers and visitors. Secondly, the O&S team must ensure the health and safety of employees, visitors and external parties at all times. As far as these tasks are concerned, the following activities were conducted in 2020.

1. Refurbishment of shaft 1

Preparations to refurbish shaft 1 have already been under way for several years. Following the appointment of an engineering company in 2017 (consortium Tractebel and BGE Germany), the project work in 2018 successfully addressed the topics of a shaft stability study, identification of the regulatory requirements, and specifications for the design and build phase. The stability of the concrete lining structure of the shaft was assessed and its stability confirmed for a period of at least 20 years by the engineering company. Also, the water tightness of the shaft lining was controlled and a program for injections in leaking cracks defined for execution in the project phase. With the national safety authorities it was agreed to base the hoisting system requirements on the German BVOS/TAS regulatory requirements, for reasons of lacking national requirements for such a system.

The contracts for the design and installation phase for the three lots (surface building, technical equipment and hoisting system) were awarded in August 2019 and a building and environmental permit for the works was granted on 8 August 2019. Three contractors are carrying out the refurbishment work: Swinnen NV from Balen, Spie Belgium from Geel and the German firm Thyssen Schachtbau. These contractors will be responsible for the infrastructure works on the surface (surface building for the hoisting system and the shaft tower with concrete foundations), the technical installations such as electricity and HVAC (heating, ventilation and air conditioning) and the refurbishment of the hoisting system and the shaft. ONDRAF/NIRAS is financing the entire project, which is estimated to cost about 7 million euros. Work on site started at the end of January 2020. Because of COVID-19 restrictions, activities in the shaft were temporarily suspended in May 2020. . The initial objective of a new operational hoisting system by the end of 2020, will therefore not be reached. It will take a few months longer before the new hoisting system will be operational (target Spring 2021). HADES is not accessible to visitors while the work is in progress, but all the necessary inspection, control and maintenance activities, as well as RD&D work can continue.

Figure 38 – Hoisting tower and machine room of the old hoisting system of shaft 1

The refurbishment operation comprises seven steps (Figure 41). At the beginning of February 2020 the hoisting cage and the cable were removed from the shaft (step 1). Then the hoisting tower, machine room and electrical distribution centre were demolished. After this the contractors started the ground works to prepare the site for the new hoisting building and install a temporary hoisting system, with which they carried out all the works in the shaft (step 2 - Figure 39). This temporary hoisting system was conform with the BVOS/TAS regulations.

Figure 39 – Temporary hoisting system

During step 3, the caged ladder and the utility piping (including electricity, ventilation, data, water and compressed air) were removed, along with the vertical guide lanes for the hoisting cage. The concrete lining of the shaft was sprayed clean and repaired where necessary (step 4). The contractors fitted new guide lanes for the main and emergency cages, ran electrical and data cables, fitted new compressed air and high-pressure water piping and renovated the ventilation channel (step 5). While the work in the shaft was in progress, the contractors constructed the new hoisting building (step 6 - Figure 40), which will be kept free of frost by blowing ventilation air from the shaft into it.

Figure 40 – New hoisting building

In late 2020 the contractors started installing the new hoisting system: the machine that will drive the hoisting system, the cable from which the hoisting cage will hang and the tower to carry it all. The concrete foundations of the tower and the shaft tower itself will be built in the first quarter of 2021. Once these have been installed, the cage will be attached to the cable and the test journeys can begin. A period of 8 weeks is foreseen in 2021 to test all functions of the hoisting system before the provisional acceptance can be pronounced by EURIDICE.

In December 2020 EURIDICE also applied at the municipality of Mol for a new licence for the operation of the URL HADES as an underground infrastructure. This because of the new hoisting system that will become operational in 2021 and because the requirements on which the current license is based have been abolished (Royal Decrees on mines).

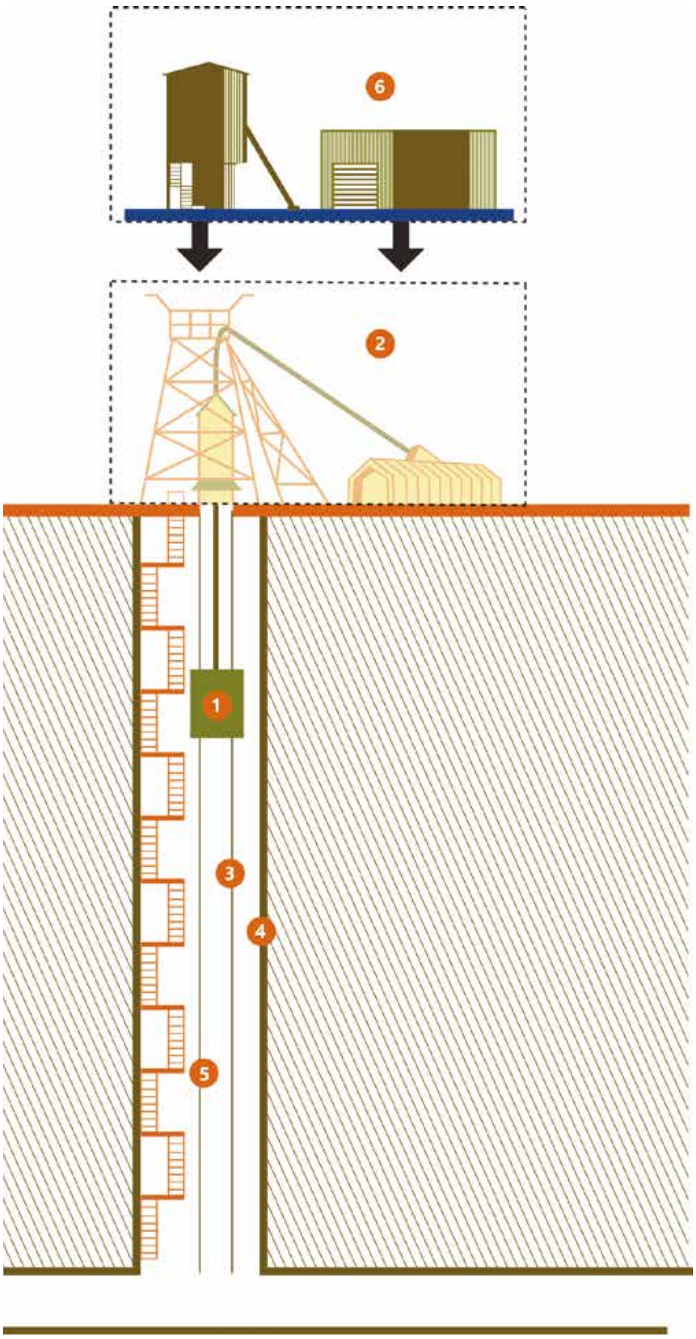


Figure 41 – Refurbishment of shaft 1 in seven steps. Step 1: Removing the hoisting cage and cable; Step 2: Demolishing the tower; Step 3: Dismantling the shaft; Step 4: Repairing the concrete lining; Step 5: New piping in the shaft; Step 6: New hoisting building; Step 7: Installing the hoisting system (planned in 2021)

2. Electrical installations

In order to comply with current legal and regulatory requirements for the safety of electrical installations in workplaces, a detailed risk analysis was carried out in 2019 on the electrical installations located in EURIDICE's above-ground and underground infrastructure. Early in 2020 a specific action plan was drawn up and implemented step by step in order to make these installations compliant with current regulations. The underground laboratory is now fully equipped with new halogen-free cabling, distribution boxes and junction points, and the old lighting fixtures have been replaced with new fixtures with LED lighting (Figure 42). The demonstration hall has also been fitted with completely new halogen-free cabling. New electrical boards have been designed, which will be installed and connected in the spring of 2021.

Figure 42 – New LED lighting in HADES

3. Network system

The network system and the associated data acquisition system in HADES and the above-ground facilities are key for the research activities at EURIDICE. In 2020 work began on reconfiguring and optimising the entire network system in order to increase its security and reliability. The new network, with data racks, switches, data cabling and fibre optic connections, is being prepared in parallel with the existing network. Once the new network is fully operational, the old cabling will be removed. The switch to the new network has already taken place above ground. Due to the complexity of the scientific experiments in HADES, it will only be possible to switch over completely in the spring of 2021.

4. Technical support for RD&D

The Operations and Safety team also gave technical support to RD&D activities for different projects.

- Connection of monitoring devices to the data-logging system in HADES.
- Technical support to the PRACLAY Seal and Heater tests.
- Technical support to the EURAD-GAS in-situ experiment.
- Technical support to external research teams (JRC-Geel, Max Planck Institute) for their experiments in HADES.
- Sampling campaigns on core samples.
- Operation of the hoisting system and technical assistance during operations in HADES.

5. Inspections, checks, periodic maintenance

Periodic inspections and preventive maintenance are required to ensure the safety of employees and visitors when using the hoisting system and the auxiliary facilities that provide access to the underground laboratory. EURIDICE technicians and AIB Vinçotte properly carried out the maintenance and daily, weekly, monthly, quarterly, semi-annual and annual checks and inspections of the whole of shaft 2.

In 2020 preparations were made to replace the suspension system of the main cage and emergency cage. The final order will be placed in January 2021.

6. Green Deal

Following the signing of the Green Deal Declaration of Intent in 2018 and delivery of the management plan in 2019, Natuurwerk started implementing the plan in the spring of 2020. An insect hotel (Figure 43), a green picnic area, flower carpets, shrubs and trees were introduced in phases. EURIDICE has applied for an environmental permit for the construction of an amphibian pool, which will be finalised in 2021.

EURIDICE will take care of periodic maintenance of the vegetation. This project ensures that a richer biodiversity will be created at the EURIDICE site.

Figure 43 – Insect hotel at EIG EURIDICE

7. Supporting third-party research

7.1. JRC-Geel

Part of the HADES URL has been leased to JRC-Geel for its research activities. It serves as an ultra-low-level radioactivity laboratory in support of European Commission policies in fields such as international standardisation, radioactive waste management and radioprotection. The contract is a Service Agreement that can be extended on a yearly basis.

Some key projects of JRC-Geel in 2020 included:
- Characterisation of reference materials for food safety and nuclear decommissioning.
- Radiotracer studies of water from the Pacific Ocean to determine ocean currents, in order to build reliable climate models.
- Analyses of Greenland ice cores and corals from both tropical waters and cold water to improve understanding of past natural and anthropogenic events.
- Measurements of radioactivity induced by cosmic rays in meteorite samples, to determine parameters such as cosmic age, terrestrial age, path through space, original size before break-up, etc.

In 2020, with support from EURIDICE, JRC-Geel produced a case book of 24 case stories, explaining the science projects conducted by JRC-Geel and collaborators in HADES over 20 years (Figure 44). It is available for download from the JRC-Geel and EURIDICE websites. A hard copy can be obtained from both organisations.

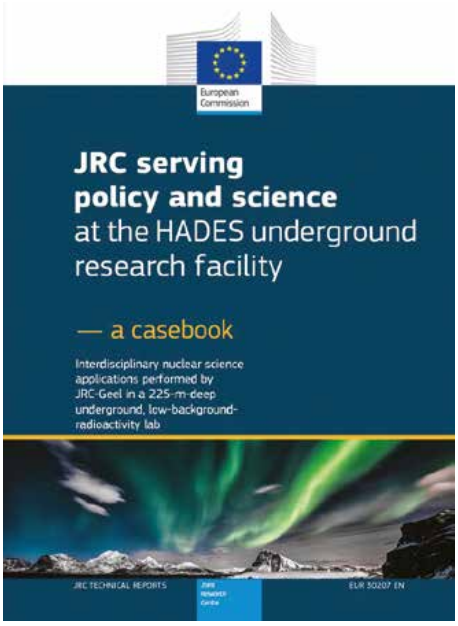


Figure 44 – Publication on JRC-Geel's activities in the HADES URL

7.2. Max Planck Institute – the LEGEND project

With the international LEGEND (Large Enriched Ge Experiment for Neutrinoless double beta Decay) partnership, the Max Planck Institute is participating in the 21st century's fundamental particle physics research. LEGEND aims to investigate whether the neutrino is its own anti-particle and whether new interactions, violating fundamental symmetries, are at work in our universe. To conduct this research project, LEGEND will look at the extremely rare natural radioactive decay of 76Ge, arranged in the form of 120 Ge detectors (200 kg in total), at the underground Laboratori Nazionali del Gran Sasso (LNGS) in Italy, starting in 2021. Some of these detectors were tested in the HADES URL.

After the successful characterisation campaign of the first four Ge detectors of LEGEND in 2019, 14 new detectors were tested in the summer of 2020. In total, about 40 kg of new detectors have already been validated. Despite the COVID-related restricted working conditions, the work was carried out safely and efficiently with limited staff on site and remote support from LEGEND collaborators. A three-month characterisation campaign took place specifically in HADES to prevent cosmic-ray activation of the detectors and ensure lower background contribution. The measurements were prepared and conducted by LEGEND collaborators, including PhD students and the JRC-Geel group (mentioned in the previous section), with the support of the EIG EURIDICE team.

All detectors are now being stored at the LNGS lab in Italy in preparation for the LEGEND experiment, due to take place in 2021. Collaboration between LEGEND and EIG EURIDICE will continue in 2021 with the delivery of additional Ge detectors.

7.3. The Royal Observatory of Belgium

Two decades ago, the Royal Observatory of Belgium (ROB) installed two accelerometers at the premises of EURIDICE, one in the HADES URL and one at the surface. These accelerometers are used to study the transfer of wave energy from the bedrock deep in the underground, through the sedimentary cover (HADES location) up to the surface. These two accelerometers, will be replaced by new ones in 2021.

In the frame of a joint PhD with the Gent University, the ROB installed five seismometers in a 3-dimensional set-up in the HADES gallery and shaft. These seismometers are linked to the seismic monitoring system of the ROB. The goal of the PhD was to study the effect of earthquakes on longitudinal underground structures. The PhD has stopped in 2019 but the ROB keeps recording the data for future research opportunities.

Communication

Communication about its activities is one of EIG EURIDICE's statutory tasks. The HADES URL and the above-ground exhibition are powerful tools for explaining the research on the safety and feasibility of geological disposal in poorly indurated clays. A visit to the underground laboratory is the best way for visitors to get an idea about the concept of geological disposal. 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.

In many ways, 2020 was an exceptional year. Due to the refurbishment of the oldest access shaft, underground visits were no longer possible. On top of that, most of the planned visits to the above-ground exhibition were cancelled due to the COVID-19 pandemic, as well as the planned 23rd Exchange Meeting. As the visits are often led by external guides, the impact on the functioning of EURIDICE was limited. The time freed up was well spent preparing EURIDICE's future communication strategy, making the transition to a new document management system and developing content for ONDRAF/NIRAS's brand-new exhibition on radioactive waste management at the Tabloo communication centre.

Figure 45 – University students visiting HADES

1. Visits

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 trips are usually combined with a tour of one of SCK CEN's facilities or a visit to ISOTOPOLIS, the information centre of ONDRAF/NIRAS and Belgoprocess in Dessel. 2019 saw the launch of 'The Bergemeesters', a new type of visit for secondary schools. 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 pros and cons 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 societal debate on this subject.

In 2020 EURIDICE welcomed 331 visitors in the course of 20 visits, most during January and February. Five of these 20 visits concerned 'The Bergemeesters' game format. Delegations from the political parties Open Vld and sp.a visited EURIDICE and the HADES URL in January to learn more about the topic of radioactive waste management. At the end of January work started on refurbishing shaft 1. From then on, underground visits were no longer possible. Due to the COVID-19 pandemic, 31 scheduled visits had to be cancelled and during the two lockdowns, no new visits were planned.

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

In the autumn of 2020 a few virtual visits were organised through videoconferencing to offer an alternative to requested visits. Examples include the Nuclear Training Programme (NTP) of ENGIE and students in the Science and Environmental Management department of the University of Liège. The virtual visit consisted of a live online presentation with EURIDICE footage, followed by a Q&A session. Feedback on these virtual visits, from both participants and organisers, was very positive, although it was clearly stated that this approach can never match the impact of a real visit.

2. Tabloo

The new communication centre for the surface disposal project in the town of Dessel will open its doors in 2022. It will host ONDRAF/NIRAS's new exhibition on radioactive waste management and SCK CEN's exhibition on its nuclear research activities. EURIDICE has been involved in preparing parts of the exhibition dedicated to the long-term management of radioactive waste. Communication coordinator Jan Rypens specifically helped develop the content of the applications about the geological timescale, the geological structure beneath the Dessel region and the module on geological disposal. This module will include a lift simulator, offering all visitors, including children, the opportunity to find out about the HADES URL and the concept of geological disposal by means of a 3D simulation.

3. Communication strategy of EIG EURIDICE 2021-2025

During 2020 the communication strategy for the coming years was formulated in interaction with both constituent members. The strategy takes into account the fact that Tabloo will open in 2022. From then on, Tabloo will be the starting point for all communications on the management of radioactive waste and on nuclear research at SCK CEN to all possible stakeholders. The new exhibition at Tabloo will replace the current ONDRAF/NIRAS exhibition at ISOTOPOLIS and the permanent exhibition at EIG EURIDICE. Socio-cultural organisations and school visits will no longer come to EURIDICE once Tabloo becomes operational. The Bergemeester game will no longer be organised at EURIDICE either.

With regard to its own communication activities, for the next few years EIG EURIDICE will focus more proactively on specific stakeholders, who will be invited to visit the HADES URL. The goal is to increase the visibility of the research activities in the HADES URL for specific academic stakeholders linked with EURIDICE's fields of expertise, and for interest groups involved in the decision-making process on the long-term management of high-level and/or long-lived waste. In addition, all communication activities will be brought in line with the communication strategy of both constituent members through Tabloo.

4. 40 years of HADES

Construction of the HADES URL started in 1980, with the first shaft excavated between 1980 and 1982, and the first gallery constructed 1983-1984. This means that the HADES URL is about to celebrate its 40th anniversary. This milestone will be an important element for the first steps in the new communication strategy. During 2020 a task force with members from EURIDICE, ONDRAF/NIRAS and SCK CEN agreed on several intitiatives that will be launched in 2021 and 2022 with the goal of increasing the visibility of EURIDICE and the HADES URL for the aforementioned stakeholders.

5. Refurbishment of shaft 1

In February 2020 work started on refurbishing the oldest access shaft. The progress made so far is described in the Operations & Safety section. EURIDICE kept its stakeholders informed by publishing its first newsletter on the project and progress of the refurbishment in July 2020. The topic was also covered in the ONDRAF/NIRAS-BELGOPROCESS newspaper, the ONDRAF/NIRAS magazine and in Gluon, SCK CEN's employee newsletter.

Figure 46 – News items on the refurbishment of shaft 1

6. Website

EURIDICE's current website was first developed seven years ago and was in need of an update. Besides updating the home page, new pages have been created on clay core requests for RD&D and on the refurbishment of shaft 1.

Figure 47 – Dedicated web page on the refurbishment of shaft 1

For the page on clay core sampling, a video was added on the sampling procedure for intact clay cores that are preserved for research purposes. This gives interested parties an idea of the operations conducted by the technical team in the underground laboratory that go hand in hand with the scientific research into the Boom Clay. Scientists wishing to request clay cores for research purposes have a good overview of the sampling procedure, handling and packaging of the fresh clay cores.

Figure 48 – Video on the Boom Clay core sampling procedure

7. Media coverage

On 30 August and 1 September an item about Belgium's long-term management of radioactive waste featured on two news programmes on Austrian national television (ORF), ZiB1 and Magazin1, which involved journalist Veronica Fillitz interviewing Sigrid Eeckhout (ONDRAF/NIRAS) and Jan Rypens at EURIDICE. The occasion was the public consultation concerning the Strategic Environmental Assessment on the long-term management of B&C waste and the outcry about it in Luxembourg and Germany.

In December 2020, on its website, RTBF posted several items on radioactive waste and its management. On 9 December #Investigation - La Une broadcast a documentary on the subject. The research at the HADES URL was only mentioned briefly. The documentary featured Sigrid Eeckhout, who was interviewed at EURIDICE.

Figure 49 – Image from the RTBF film report on radioactive waste management with participation from EIG EURIDICE

8. Participation in external events, conferences and meetings

Due to the COVID-19 pandemic, many events and conferences, such as the 2020 Clay Conference, were either cancelled or postponed. Within the context of the EURAD – HITEC project, EURIDICE took part in the yearly progress meeting (virtual), which was held on 9 and 10 June 2020. EURIDICE was also represented at a virtual working meeting organised by the IAEA on 9 June 2020 to establish the final planning schedule to finalise the compendium.

Knowledge management

The aim of knowledge management at EIG EURIDICE is primarily to generate, store and pass on knowledge about its activities, in support of the geological disposal programme of high-level and long-lived waste in Belgium.

Over the past few years EURIDICE has launched several initiatives relating to document management, instrumentation and data management, the HADES inventory, an inventory of technical/scientific knowledge and expertise, knowledge transfer and validation of knowledge. In 2020 EURIDICE started developing a strategy on knowledge management, in interaction with the knowledge managers of its two constituent members, ONDRAF/NIRAS and SCK CEN. Various aspects of knowledge management within EURIDICE were defined and are briefly described below. Specific achievements in 2020 are listed at the end of this section.

DATA MANAGEMENT

Different complementary tools are used for the technical inventory of instrumentation in HADES, for data management and for visualisation of recorded data:

- Daily, the standard data management system that has already been in use for several decades.
- GSIS (GeoScientific Information System), which is an integrated database that centralises all data concerning drilling, drill 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.
- LabTool, a software application developed for the follow-up of long- and short-term experiments. This tool extends our capabilities compared with Daily, as it combines inventory management (instrumentation, sensors, calibrations, maintenance notifications, etc.) with data management (raw data, data validation, data visualisation). LabTool is, in turn, linked with GSIS.

INFORMATION MANAGEMENT

This aspect concerns processed data based on computer models, and reports. EURIDICE is currently looking at how to optimally centralise processed data from computer modelling.

DOCUMENT MANAGEMENT

Alexandria, SCK CEN's document management system, has recently been implemented at EURIDICE. A new document management structure was created, in line with EURIDICE's main processes (general management, operations & safety, RD&D and communications). Besides Alexandria, EURIDICE also uses Vignette, the document management system of ONDRAF/NIRAS, to share the outcome of the different RD&D projects.

Scientific output is stored in 'Roma', SCK CEN's system for archiving all scientific output. A search engine is available on EURIDICE's website and this can be used to find references to the most important publications.

MANAGEMENT OF TECHNICAL/SCIENTIFIC KNOWLEDGE AND EXPERTISE

This involves (1) insight into processes, parameters and conditions that are important in the operation of HADES and in the related research, and (2) insight into what is important in the EURIDICE knowledge domains for the safety and feasibility of geological disposal.

The inventory of technical/scientific knowledge and expertise focuses on the following areas:

- Instrumentation, measurement techniques and data management.
- The THM/THMC behaviour of geological materials (mainly the Boom Clay) and artificial materials (such as bentonite and concrete), and interface interactions between the materials.
- Excavation and construction techniques for underground disposal facilities.
- The environment of the HADES URL (temperature, relative humidity, etc.).

Via www.euridice.be, the 'scientific outcome' section is accessible to online visitors. This is intended for anyone with a scientific background and gives an overview of the main conclusions and reports that cover scientific/technical knowledge and expertise. The annual Activity Reports provide an inventory over time of the various RD&D activities that contribute to this knowledge and expertise.

KNOWLEDGE TRANSFER
Transfer of knowledge primarily concerns aspects such as the construction and operation of HADES, and related RD&D projects, mainly those on the THM/THMC behaviour of the Boom Clay and engineered barriers and the interactions between them.

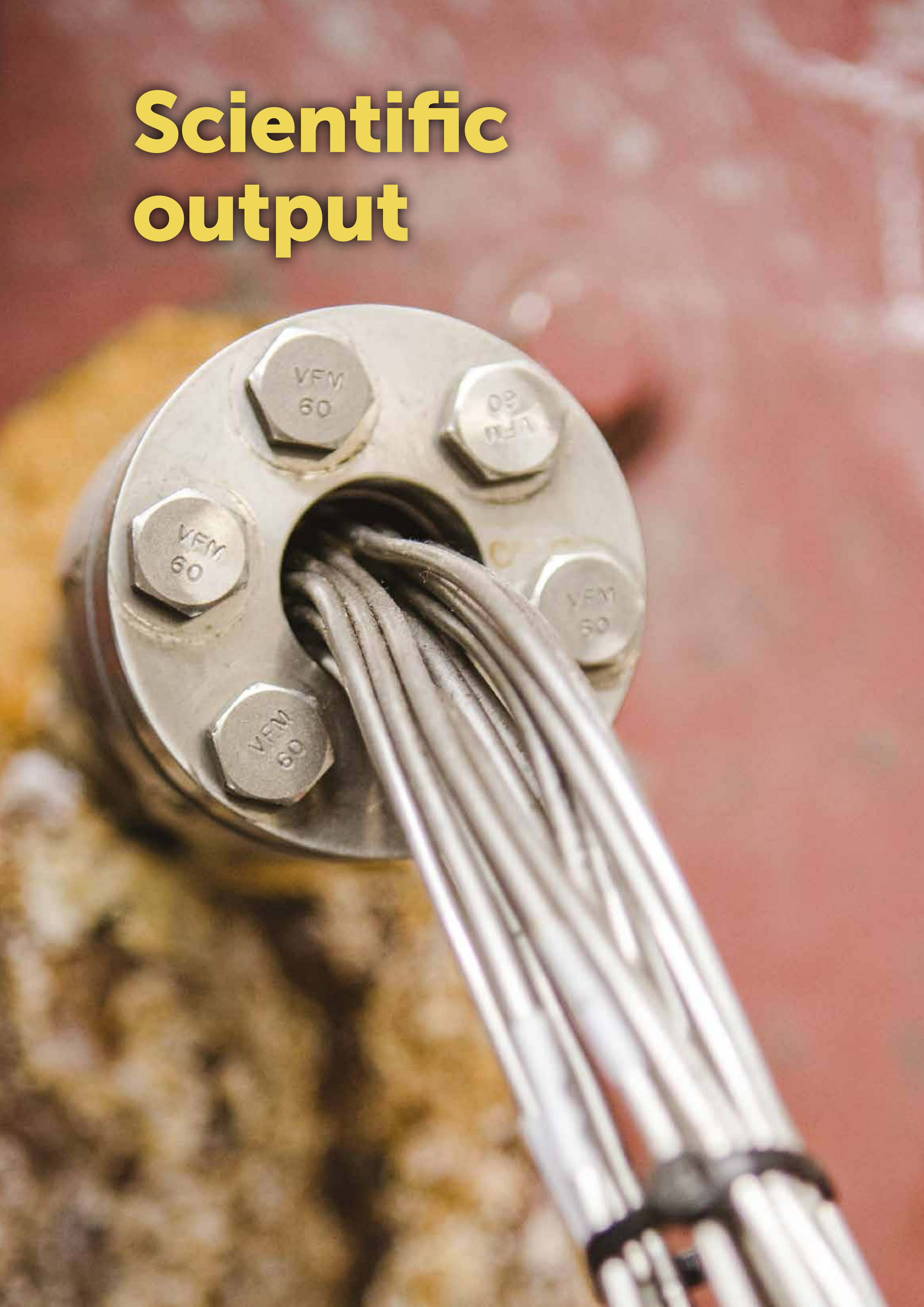
Within EURIDICE, education and training (including on-the-job training of new recruits) and skills management are essential tools for transferring knowledge between different generations of employees.

VALIDATION OF KNOWLEDGE
This is achieved through scientific output, contributions to international projects, workshops and conferences, and through related training programmes. The aim of increasing EIG EURIDICE's scientific visibility both nationally and internationally was formalised in 2020 in a dedicated document approved by both constituent members.

THE FOLLOWING WAS ACCOMPLISHED IN 2020:

- LabTool was gradually implemented, with priority for active set-ups (e.g. ATLAS, PRACLAY and MEGAS), all components of which were input into the LabTool database in a well-organised structure.
- Alexandria, the new document management system at EURIDICE, was implemented and all documents were transferred in a new document structure.
- The paper archive inventory was completed.
- As EURIDICE contributed to the IAEA Compendium of R&D activities in URFs, the RD&D platform decided to use this Compendium as the basis for an inventory of in-situ experiments in HADES and the knowledge gained from each individual experiment (current status of the HADES facility). EURIDICE carried out a completeness check of the IAEA Compendium and all references are being centralised in Alexandria and Vignette.
- A database of laboratory tests on the THM behaviour of the Boom Clay was established, with indication of the test objectives and references.
- A list of the main THMC parameters of the Boom Clay was compiled, with indication of the key references.

Scientific output



JOURNAL PAPERS

Babaei S., Seetharam S., Muehlich U., Dizier A., Steenackers G., Craeye B. A multiscale framework to estimate water sorption isotherms for OPC-based materials. *Cement and Concrete Composites*. 2020. Vol. 105. pp. 1-13. (https://doi.org/10.1016/j.cemconcomp.2019.103415)

Babaei S., Seetharam S., Dizier A., Steenackers G., Craeye B. An analytical framework for estimating drying shrinkage strain of OPC based hardened cement paste. *Cement and concrete composites*. Volume 115, January 2021. (https://doi.org/10.1016/j.cemconcomp.2020.103833)

Dizier A., Chen G., Verstricht J., Li X.L., Sillen X., Levasseur S. The large-scale in situ PRACLAY heater test: First observations on the in situ thermo-hydro-mechanical behavior of Boom Clay. International Journal of Rock Mechanics and Mining Sciences. International Journal of Rock Mechanics and Mining Sciences. Volume 137, January 2021. (https://doi.org/10.1016/j.ijrmms.2020.104558)

Chen G.J., Dizier A., Li X.L., Verstricht J., Sillen X., Levasseur S. Numerical prediction of the large-scale in situ PRACLAY heater test in the Boom Clay. Rock Mechanics and Rock Engineering. Accepted for publication.

Chen G.J., Li X.L., Sillen X., Levasseur S. Thermal characterization of the Boom Clay based on numerical interpretation of both a small-scale and a large-scale Heater test in HADES URF, Belgium. Acta Geotecnica. Submitted.

CONTRACT REPORTS

Chen G. Two dimensional coupled THM modelling of the PRACLAY heater test : An interpretation after 3-year stationary heating. EUR-20-055 /ER. ESV EURIDICE GIE, Mol, Belgium. 2020. 64 p. (External report)

Dizier A. Thermo-hydro-mechanical analysis of a C-waste geological disposal facility (GDF) : Technical report. EUR-18-017/ER. ESV EURIDICE GIE, Mol, Belgium. 2020. 48 p. (External Report)

Dizier A., Chen G., Li X.L. Mechanical analysis of the Seal. EUR-PH-20-059/IR. ESV EURIDICE GIE, Mol, Belgium. 2020. 37 p. (Internal Report)

Dizier A., Chen G., Li X.L. Initial condition data report before the switch-on of the PRACLAY Heater test. EUR-PH-20-62/IR. ESV EURIDICE GIE, Mol, Belgium. 2020. 68p. (Internal report)

Verstricht J. PRACLAY structure and sensor coordinates. EUR-PH-20-060 /ER. ESV EURIDICE GIE, Mol, Belgium. 2020. 66p. (External report)

PRESENTATIONS

Dizier A., Chen G., Verstricht J., Li X.L. 2020. In situ THM testing at high temperature: Poorly indurated clays (Boom Clay). EURAD School for Radioactive Waste Management, Liège, Belgium. (Presentation)

Awarkeh M., Cui Y.J., Yu L., Levasseur L., Dizier A. 2020. Investigation of the long-term behavior of Boom Clay. Day of the PhDs. SCK CEN, 13 November 2020. (Presentation)

Larion Y., Chen G.J., Seetharam S., Massart T.J., Zlotnik S., Díez P. 2020. Reduced order modelling for coupled geomechanics problems. Day of the PhDs. SCK CEN, 13 November 2020. (Presentation)

List of accronyms

ANDRA	Agence Nationale pour la Gestion des Déchets Radioactifs (FR)
CLIPEX	CLay Instrumentation Programme for the EXtension of an underground research laboratory
EBS	Engineered barrier system
EC	European Commission
EDZ	Excavation-damaged zone
EURAD	European Joint Programme on Radioactive Waste Management and Disposa
EURIDICE	European Underground Research Infrastructure for the Disposal of nuclear waste in Clay Environment
FANC	Federal Agency for Nuclear Control (BE)
FEM	Finite Element Method
GSIS	GeoScientific Information System
HADES	High-Activity Disposal Experimental Site
ISOTOPOLIS	ONDRAF/NIRAS's information centre about radioactive waste management, located in Dessel
LIMS	Lab Information Management System
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)
NBS	Natural barrier system
ONDRAF/NIRAS	Belgian Agency for Radioactive Waste and Enriched Fissile Materials (BE)
PRACLAY	Preliminary Demonstration Test for Clay Disposal
ROM	Reduced Order Model
SCK CEN	Belgian Nuclear Research Centre (BE)
STORA	Studie en Overleggroep Radioactief Afval in Dessel (local citizen platform on nuclear waste issues in Dessel)
THM	Thermo-hydro-mechanical
THMC	Thermo-hydro-mechanical-chemical
UPC	Universitat Politècnica de Catalunya (ES)
URL	Underground research laboratory
URF	Underground research facility
W&D	Waste and Disposal, an SCK CEN expert group

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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