

2019

Activity Report



ESI EURIDICE EIG

2019

Activity Report



ESV EURIDICE EIG

Activity Report 2019

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Approved by:

Hildegarde Vandenhove, Board of Governors

Marc Demarche, Chairman of the Board

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General foreword

Marc Demarche, Chairman of the Board of EIG EURIDICE

Dear reader,

EIG EURIDICE is the Economic Interest Grouping between ONDRAF/NIRAS and SCK CEN. It is responsible for managing and operating the HADES underground research laboratory (URL), carrying out research and development activities for the geological disposal of radioactive waste in deep clay formations and communicating its activities. This Activity Report provides a comprehensive overview of the main developments and results relating to the statutory tasks of EIG EURIDICE in 2019. The scientific research is divided into two parts. Part 1 is the most extensive and focuses on the activities within the framework of the ONDRAF/NIRAS research programme for geological disposal. Part 2 homes in on EURIDICE's activities in support of ONDRAF/NIRAS's programme for the surface disposal of low-level radioactive waste.

The process of strategic review of the operation of EIG EURIDICE and its vision for the future with its constituent members concluded in 2019, with the Boards of Management of SCK CEN and ONDRAF/NIRAS approving its new Statutory Rules and Internal Rules and Regulations. These Statutory Rules stipulate continued collaboration between SCK CEN and ONDRAF/NIRAS through the EIG until 2045. They also emphasise the importance of knowledge management for EIG EURIDICE's activities and tasks, and the key role of the HADES underground laboratory in this respect. The members also reached an agreement on property rights and the future use of the HADES URL both in situations of collaboration through the EIG EURIDICE and in future scenarios.

Through the newly established RD&D platform within the EIG EURIDICE organisation, the constituent members, together with the EURIDICE team, discuss and determine the direction of future research in HADES and the strategy for knowledge management. In 2019 a compendium of the main RD&D experiments in the HADES URL was drawn up as part of an international IAEA project. This compendium will form the basis of our future knowledge management activities: it will provide structure and a starting point for assessing the available knowledge from past experiments and the possible future use of these experiments.

With a view to the members' continued collaboration through EIG EURIDICE and future RD&D use of the HADES URL, EURIDICE is also investing in the refurbishment of shaft 1, which dates back to the early 1980s. In 2019 the public tender procedure for the design and construction of the shaft 1 project culminated in the award of contracts for the three lots: the surface building, the technical equipment and the hoisting system itself. The project kick-off meeting with all parties took place in September 2019 and on-site work will start in early 2020.

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 fourth year of heating at 80°C was successfully completed in 2019. The experimental set-up has proved to be robust and reliable: the hydraulic seal and the heating system are performing 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 is a key objective of the experiment.

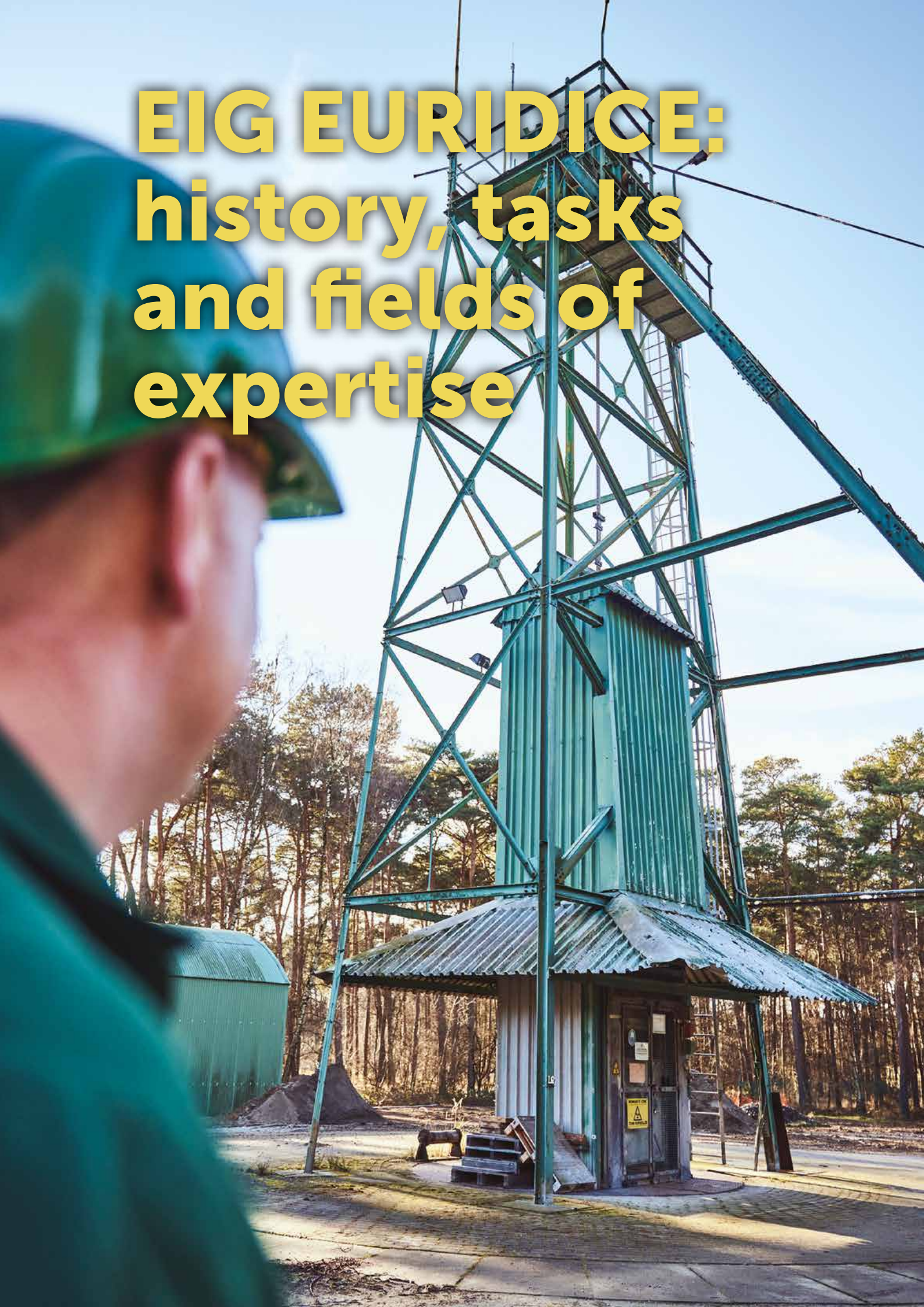
The many years of preparation and the 10-year heating phase of the PRACLAY Heater test significantly contribute to ensuring continuity of knowledge and expertise within the organisation and the programme. To share and disseminate this knowledge, EURIDICE regularly informs the stakeholders about how the test is progressing through newsletters, external reports and numerous presentations. In the course of 2018 and 2019 EURIDICE prepared a number of reports with a detailed evaluation of the scientific findings and of the performance and reliability of the measuring instruments since the start of the Heater test. Scientific papers on the PRACLAY Heater test will be submitted for publication in the first half of 2020.

In 2019 *De Bergemeesters* was tested and successfully launched, an interactive approach for school visits during which students discuss the pros and cons of constructing a geological repository in a local community. This is the start of a new type of visit, with more focus on societal acceptance of geological disposal. Our aim with this interactive approach is to ensure greater involvement by the future generations that will be responsible for developing and implementing the long-term management strategy for radioactive waste.

2020 will mark the 40th anniversary of the HADES URL and the refurbishment of the shaft 1 hoisting system. We will also reach the mid-term of the PRACLAY Heater test. EIG EURIDICE and its two constituent members are preparing a number of events to showcase these milestones and 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.

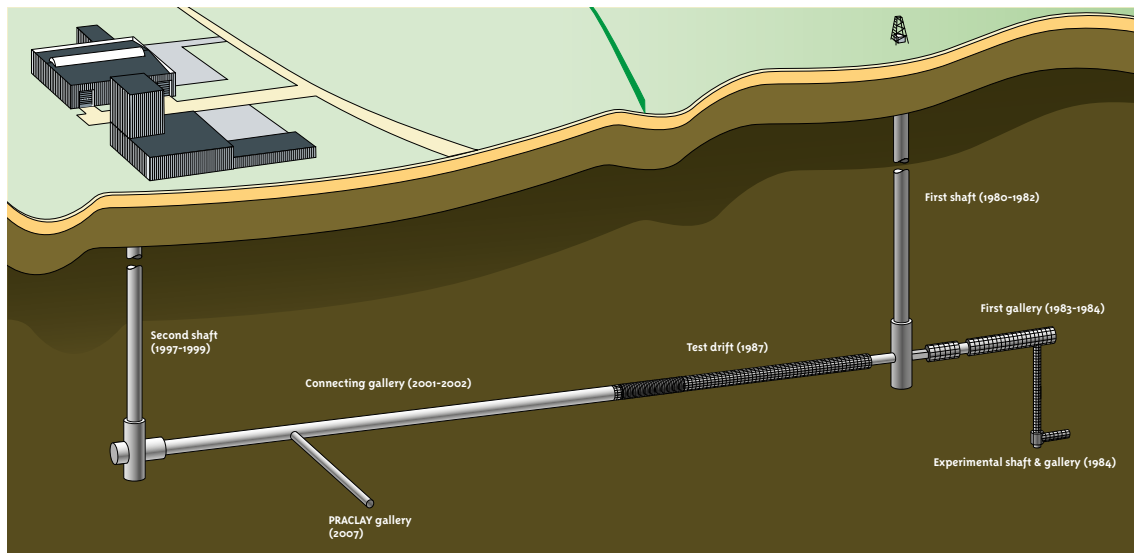


Figure 1 - The underground research laboratory HADES (High-Activity Disposal Experimental Site)

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 nearly 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 will be the main barrier for radionuclide migration in a geological disposal system, reducing the excavation-damaged zone (EDZ) around the excavated galleries is a key objective and relates directly to the safety of a disposal system.

The second field of expertise of EIG EURIDICE involves understanding the thermo-hydro-mechanical (THM) behaviour and characterisation of a clay host rock and engineered barrier system (EBS) (concrete buffer comprising supercontainer, concrete liner, clay-based seal materials such as bentonite, etc.), including all disturbance processes 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 the repository is essential so as to determine to what extent these processes could affect the capacity of the clay to contain the radioactive substances and to isolate the radioactive waste. The most important project in this area is the large-scale PRACLAY experiment. Here, the combination of the hydro-mechanical disturbances due to excavation of galleries and the further coupled thermo-hydro-mechanical disturbance due to heat production, as in the case of the disposal of high-level vitrified waste or spent fuel, are studied on a large scale.

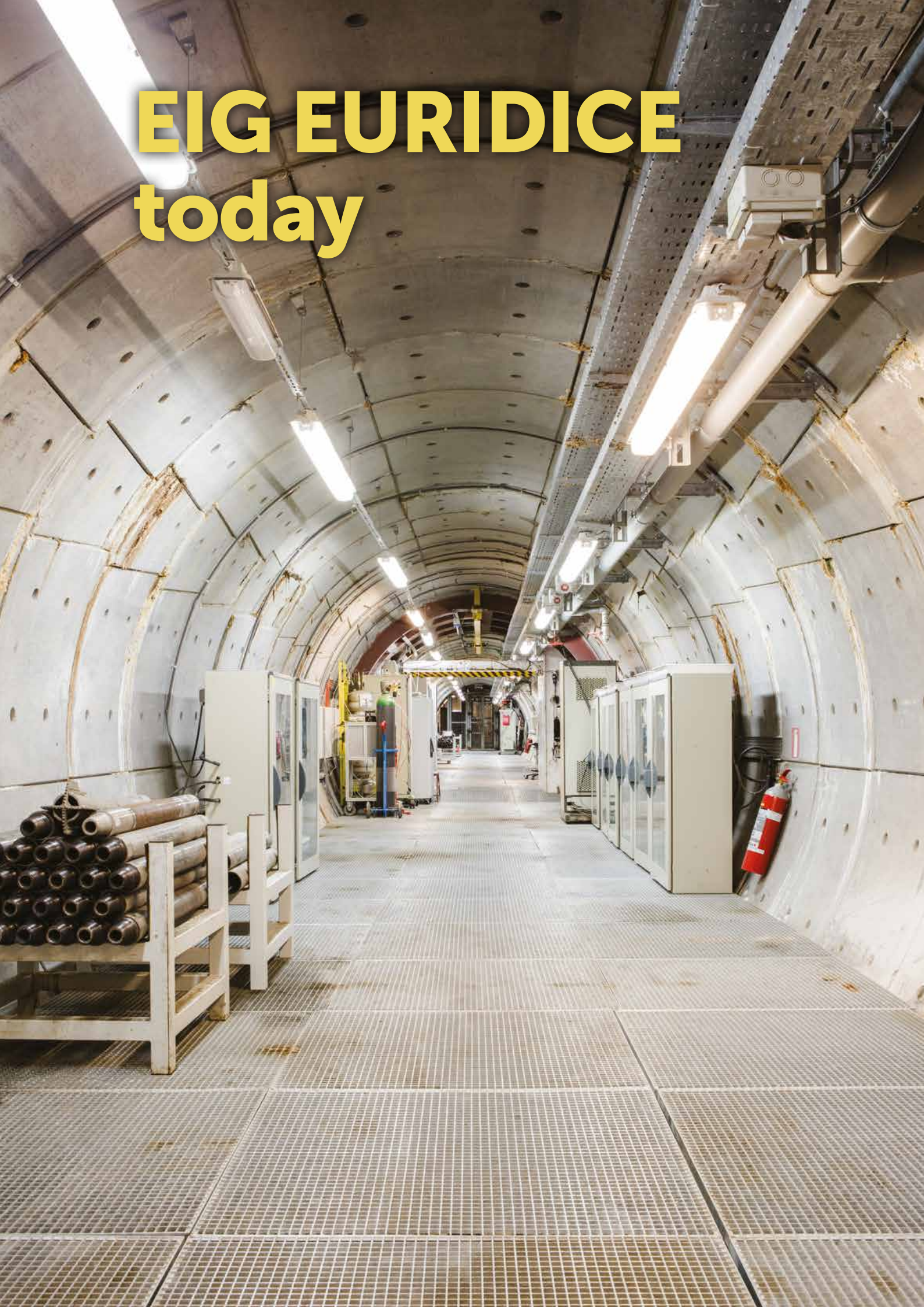
With its RD&D activities and fields of expertise, EIG EURIDICE contributes to the national programme for high-level and long-lived waste disposal managed by ONDRAF/NIRAS. In 2013 ONDRAF/NIRAS finalised its RD&D plan on geological disposal (NIRON-TR 2013-12 E), describing the main achievements and future 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's scientific activities in 2019 mainly focused on following up the PRACLAY Heater test. Since the temperature at the interface between the concrete lining and the clay reached the target of 80°C in August 2015, the power of the heating system has been systematically adjusted to keep the temperature constant at 80°C (stationary heating phase). This Activity Report provides an overview of the main observations regarding the PRACLAY Heater test since switching on the heating system on 3 November 2014 up until the end of 2019, 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 2019 the PRACLAY Heater test had been running for more than five years. The experimental set-up is still working perfectly. The test components are evolving as expected. Over the years, continuous efforts have been made to improve the interpretation of the PRACLAY Heater test by modelling, which enables us to improve and confirm the THM characterisation of the Boom Clay. In 2019 this resulted in two reports, one on the improved interpretation of the measured temperature and the other on the improved interpretation of the measured pore water pressure. In addition, two papers were prepared on the PRACLAY experiment for publication in international peer-reviewed journals (submission in early 2020).

A specific thermo-hydro-mechanical-chemical (THMC) characterisation programme on the Boom Clay is being run in parallel with the PRACLAY experiment, in collaboration with various universities and laboratories as part of several PhD research projects. EIG EURIDICE is involved in the supervision of these projects.

Furthermore, EIG EURIDICE takes part in several European research projects. Firstly, EURIDICE contributes to EC Modern2020, a project on monitoring strategies, technologies, demonstrations and stakeholder interaction in the context of geological radioactive waste repositories. Furthermore, as part of the European Joint Programme on Radioactive Waste Management and Disposal (EURAD), EURIDICE is involved directly in 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 by providing scientific and technical support to SCK CEN's W&D expert group. Finally, EURIDICE contributed to the IAEA "Compendium of Results of RD&D Activities carried out at Underground Research Facilities (URFs) for Geological Disposal".

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 board members as at the end of 2019 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
- Hildegard 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.

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

In 2019, in interaction with its constituent members SCK CEN and ONDRAF/NIRAS, EIG EURIDICE completed the strategic review of its statutory tasks, organisation and operation, with a view to improving its future performance in support of its two members. During 2018 and 2019 formal decisions were taken by the Management Board of EIG EURIDICE and by the Boards of SCK CEN and ONDRAF/NIRAS for the approval of:

- The new Statutory Rules of EIG EURIDICE;
- The new Internal Rules and Regulations of EIG EURIDICE;

With the new **Statutory Rules** for EIG EURIDICE, the most important changes are:

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

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

EIG EURIDICE has been ISO-certified according to the ISO 9001 standard for Quality Management since 2007. The current certificate is valid until 23 September 2021. On 20 September 2019 an external follow-up audit according to ISO 9001:2015 was performed by DNV-GL with a focus on General Management, Communication, RD&D and Measurements & Monitoring.

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 2019 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 - scientific collaborator
Guangjing Chen - scientific collaborator
Dries Nackaerts - technical/scientific collaborator
Jan Verstricht - scientific collaborator
Wim Bastiaens - scientific collaborator

Operations and safety process:

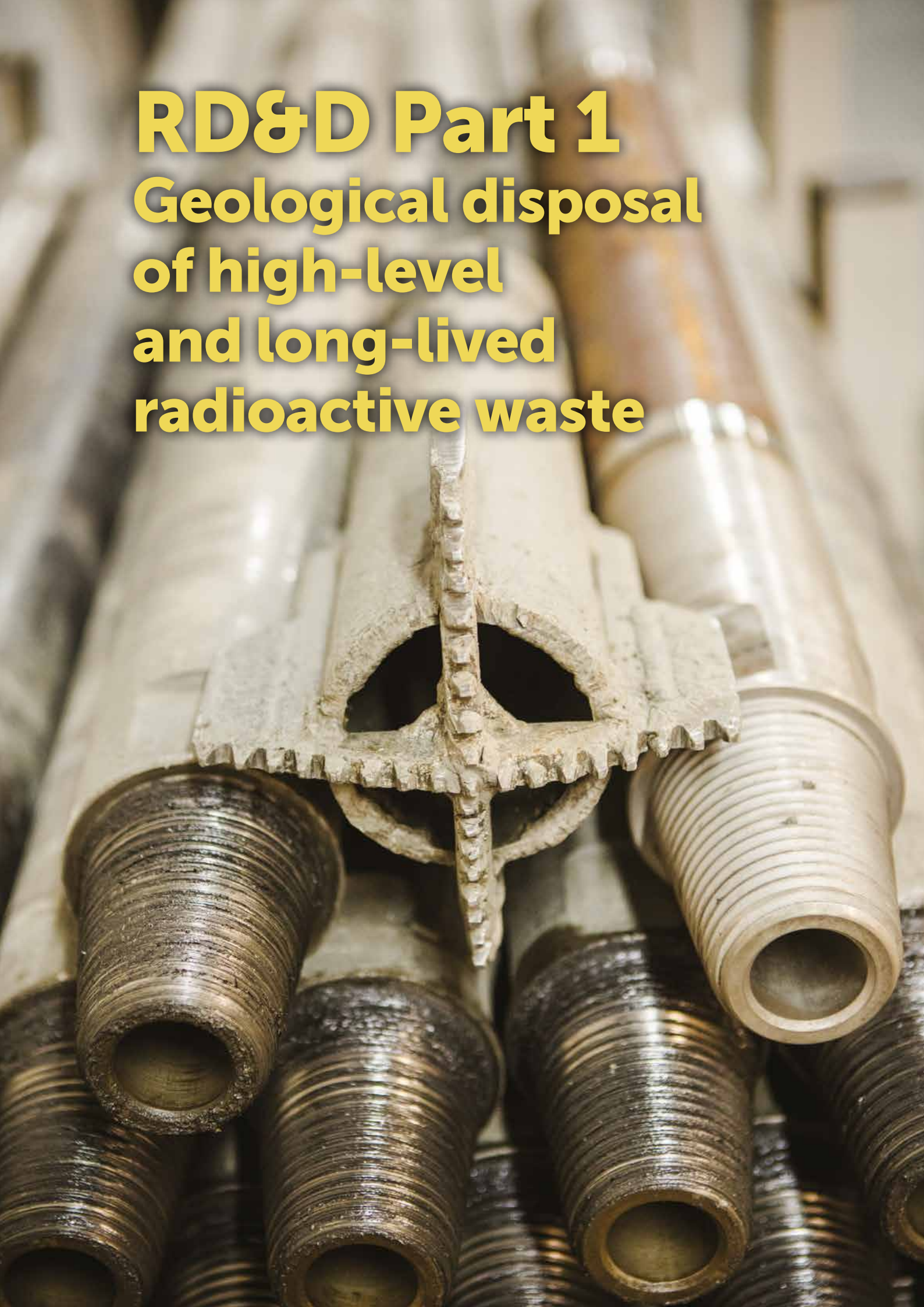
Kevin Schuurmans - manager
Luc Mariën - project engineer
Dries Nackaerts - technical/scientific collaborator
Hendrik Huysmans - technical collaborator
Christian Lefèvre - technical collaborator
Johan Peters - technical collaborator
Bert Vreys - technical collaborator

Communication process:

Jan Rypens - coordinator
Els van Musscher - communication collaborator

RD&D Part 1

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



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 Safety and Feasibility Cases, which are part of 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 (length, time, temperature) in such a way that it is representative of the conditions that would be expected in a high-level waste repository. 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.

By the end of 2019 the PRACLAY Heater test had been running for more than five years. The experimental set-up is still working perfectly. The test components are evolving as expected.

1.1. Test set-up

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

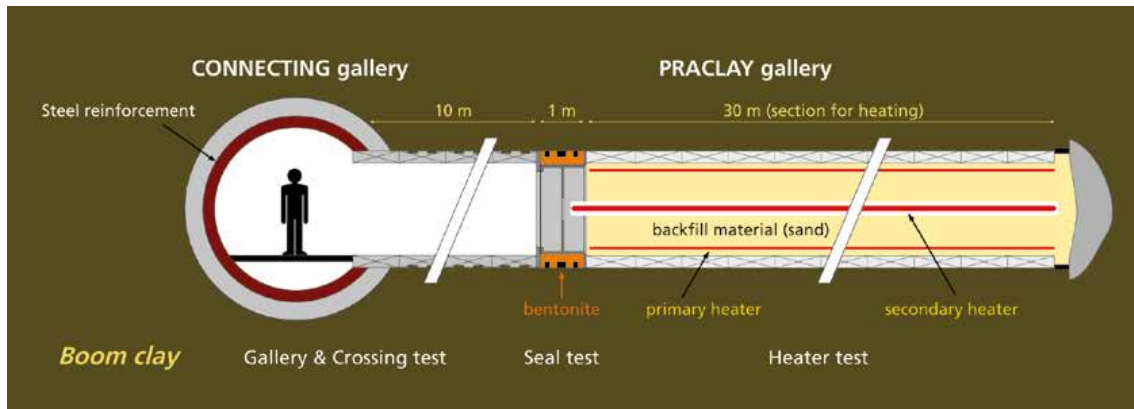


Figure 2 - Design of the PRACLAY experiment

HEATING SYSTEM

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



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

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

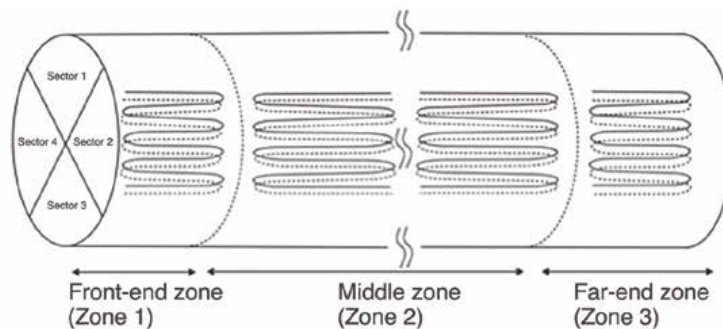


Figure 4 - The primary heating system is composed of three zones, each divided into four sections

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

A control system regulating the heating power as a function of measured and target temperature is part of the heating system. The primary and secondary heating systems each have their own control system. The primary heater is regulated in different ways for the three different zones to ensure that the temperature is kept as constant and uniform as possible (80°C at the interface between the gallery lining and the Boom Clay) over the whole heated zone during the stationary heating phase. The secondary heater can only deliver the same power output over its entire length, and this has to be regulated over time to ensure the same thermal boundary conditions (i.e. a constant temperature of 80°C at the interface between the gallery lining and the Boom Clay). The value of this power output will be set at the time of the switch-over, 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 5).

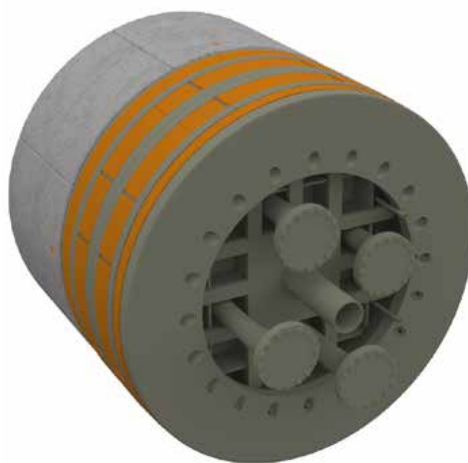


Figure 5 - 3D view of the seal with a central steel cylinder and an annular ring of bentonite (orange) against the clay

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

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

To meet these specifications, firstly, the initial dry density of the bentonite was carefully determined, as this parameter determines its swelling pressure and its final saturated hydraulic conductivity. The desired initial dry density was determined by scoping calculations, taking into account the technological void and the interaction with the Boom Clay. An initial dry density of 1.8 tonnes/m³ was selected. Secondly, the bentonite needs to be sufficiently hydrated. The bentonite seal has been hydrated since its installation in January 2010 by pore water coming from the Boom Clay and by water injected through filters placed on the outer surface (extrados) of the steel cylinder since April 2010. Different kinds of instruments were incorporated into the bentonite rings during installation to monitor the water injection rate as well as stress (swelling pressure) and pore water pressure in the bentonite and in the Boom Clay around the seal. The instruments are grouped into sections A, B and C (Figure 6).

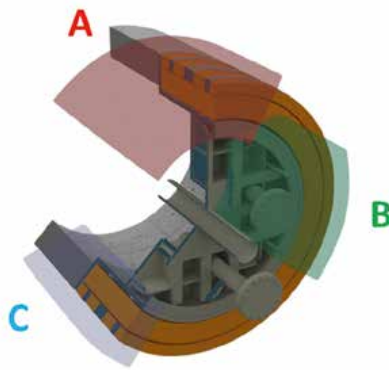


Figure 6 - Various instruments inside the bentonite, grouped into sections A, B and C

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

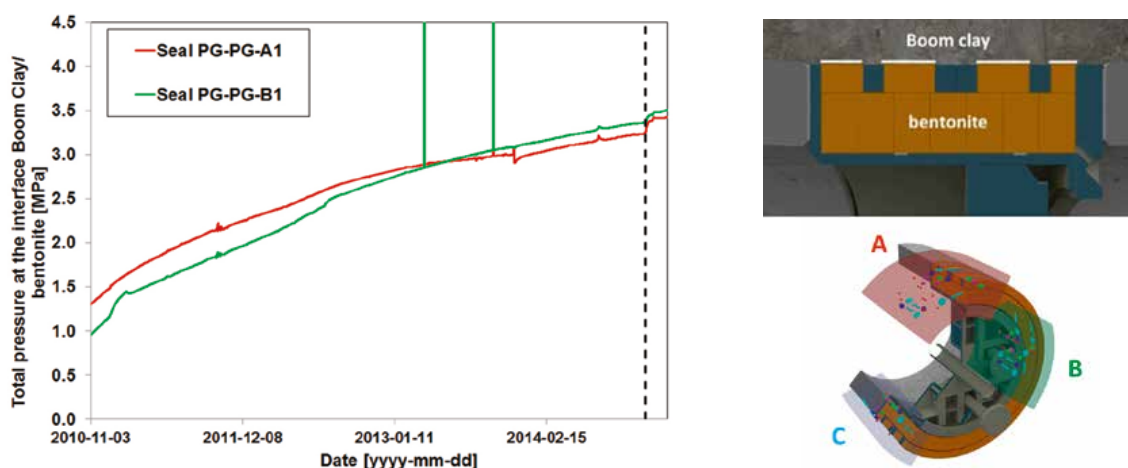


Figure 7 - Radial stresses measured at the interface between the bentonite and the Boom Clay sidewall (white line in insert), for sections A, B and C. The vertical dashed line marks the date of the switch-on.

BACKFILL SAND

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

MONITORING, INSTRUMENTATION AND DATA MANAGEMENT

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

INSULATION DOOR

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

1.2. 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 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. The management guide was completely reviewed and updated in 2016.

NUMERICAL MODELLING

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

Prior to the Heater test, predictive modelling of the PRACLAY Heater test was performed, the so-called "numerical predictions", which involved 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.

1.3. Observations since the switch-on until the end of 2019

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 a constant 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 2019 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 8 and Figure 9). It was also decided that the power for Zone 1 would mirror that for Zone 2 in spite of the end effect of heat dissipation so as to avoid overheating of the seal structure (safety precaution).

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

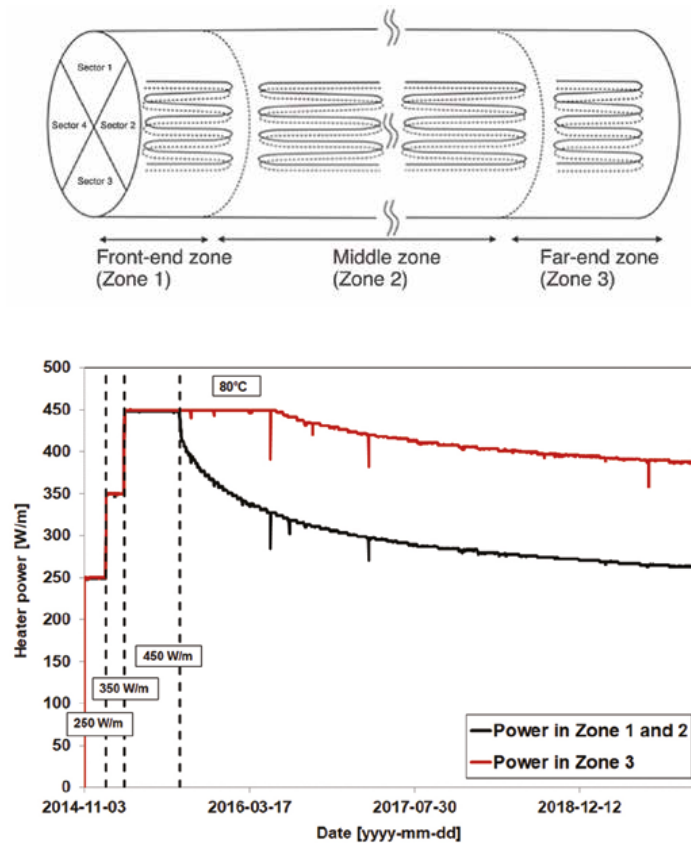


Figure 8 - Evolution of the power in watts per metre (W/m) in the three zones. The power in Zones 1 and 2 was decreased once the temperature in Zone 2 reached 80°C (measured by $T_{int,1}$). The power in Zone 3 was decreased with a delay of a couple of months once Zone 3 reached 80°C (measured by $T_{int,2}$).

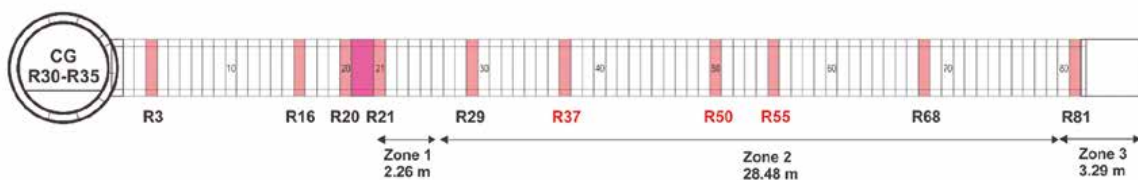
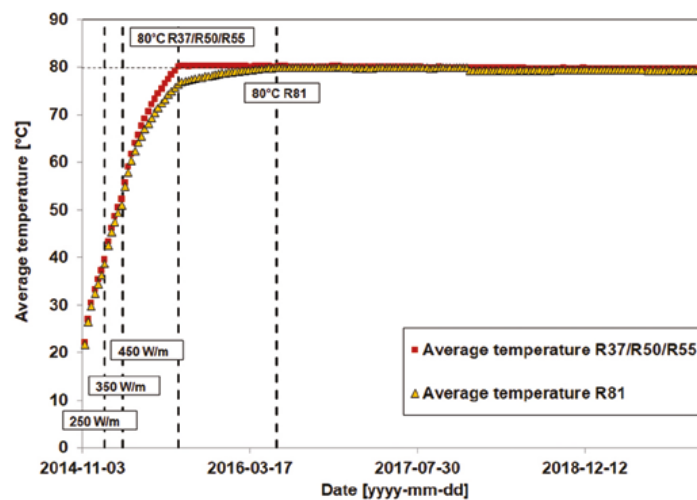


Figure 9 - Average temperature evolution measured using the extrados sensors in R37, R50 and R55 ($T_{int,1}$) and R81 ($T_{int,2}$)

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

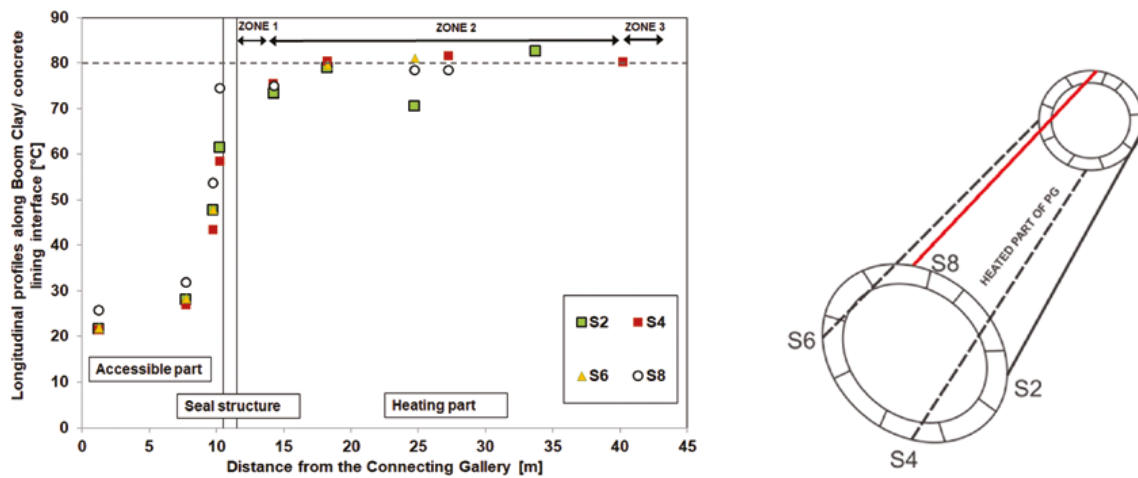


Figure 10 - Longitudinal profiles of the temperature along the extrados of the PRACLAY gallery

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 and relative higher rigidity of the concrete lining and the Boom Clay), an excess pore water pressure in the system is induced inside the PRACLAY gallery. This rise in pore water pressure in the backfilled part of the PRACLAY gallery is shown in Figure 11. During the start-up phase of the Heater test, the pore water pressure rose quickly at the beginning of each heating step, followed by a more gradual increase, due to progressive dissipation of water pressure 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.

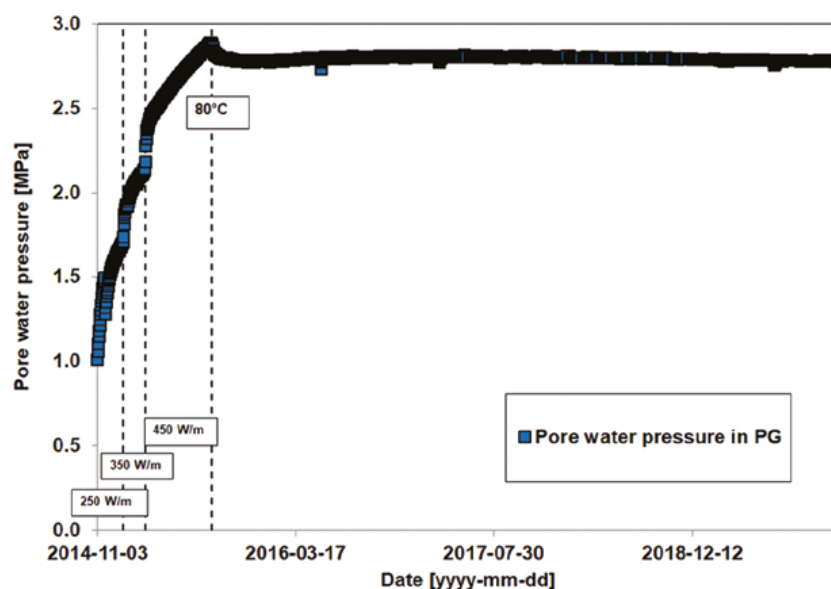


Figure 11 - Pore water pressure evolution in the backfilled part of the PRACLAY gallery

BOOM CLAY RESPONSES

Porous media with low permeability, such as the Boom Clay, can experience a substantial increase in pore water pressure as a consequence of a temperature rise due to the differential thermal 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 12).

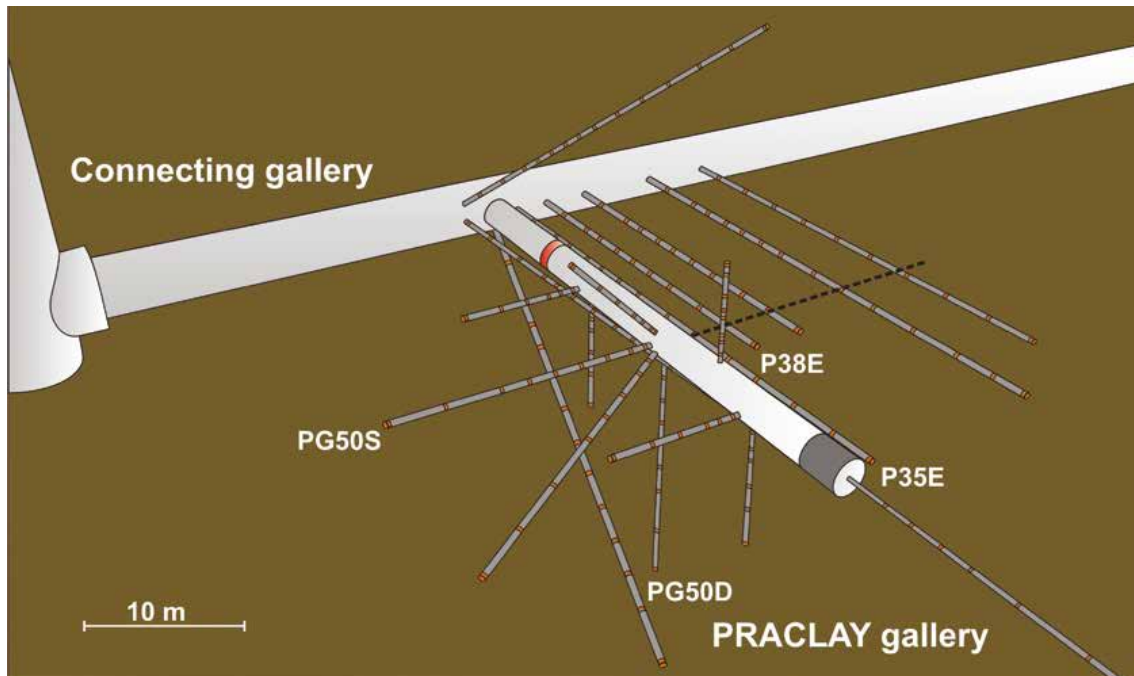


Figure 12 - 3D view of the instrumented boreholes from the PRACLAY gallery and the Connecting gallery

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

It was observed that, at the end of 2019, the thermally affected zone had extended to a depth of more than 15 m into the Boom Clay in the horizontal direction (Figure 14a). Comparison with last year's profile showed that the increase in temperature is becoming slower over time and that the thermally affected zone is extending very slowly.

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 13 and Figure 14b). By comparing the pore water pressure profiles at a distance of around 5 m from the gallery intrados in 2017, 2018 and 2019 (Figure 14b), it can be observed that the peak of maximum excess pore water pressure in the Boom Clay was reached in 2017. Since that time, the excess pore water pressure has been dissipating into the surrounding environment and the pore water pressure has decreased slightly close to the concrete lining.

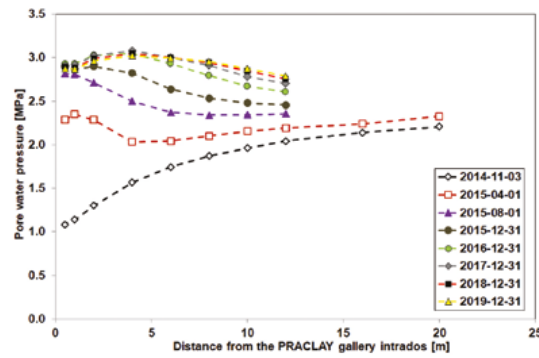


Figure 13 - Evolution of the pore water pressure profiles in the vertical direction at the middle section of the heated part of the PRACLAY gallery (along borehole PG50D)

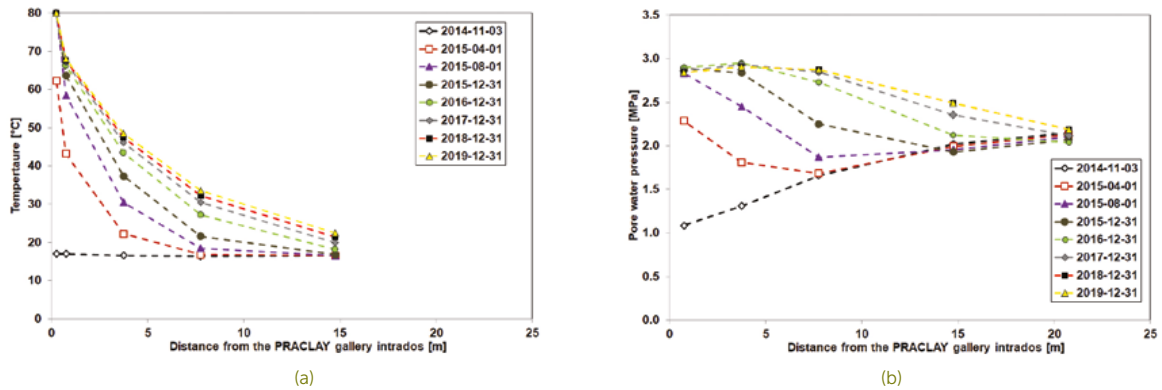


Figure 14 - Temperature and pore water pressure profiles in the horizontal direction at the middle section of the heated part of the PRACLAY gallery (measured from boreholes drilled from the Connecting gallery)

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

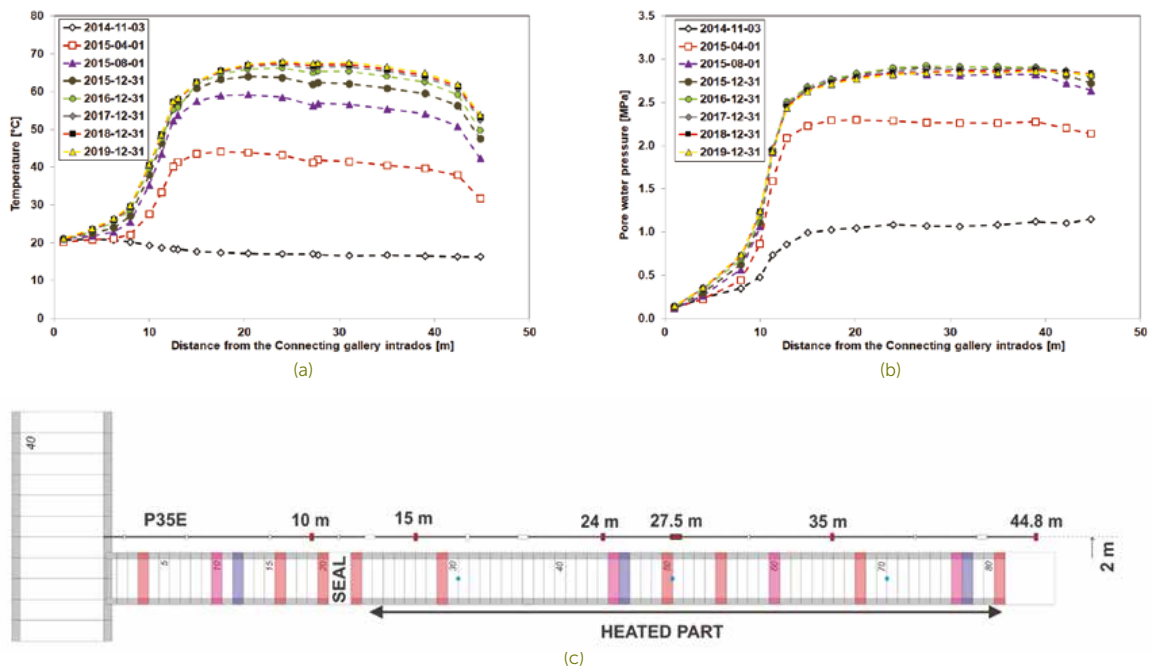


Figure 15 - Temperature and pore water pressure profiles in P35E

The temperature and pore water pressure at a distance of 5 m from the axis of the PRACLAY gallery (measured by the sensors in borehole P38E; see Figure 12) can be seen in Figure 16. The pressure in this borehole reached 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.

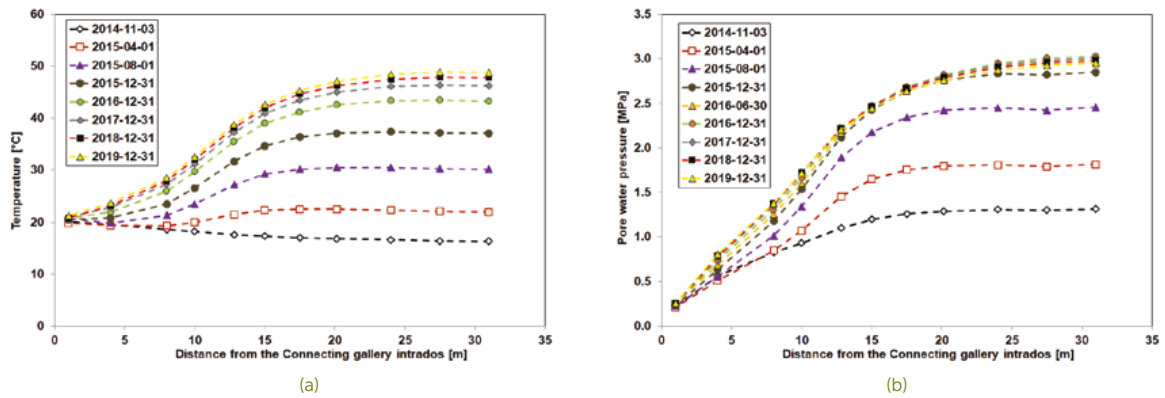


Figure 16 - Temperature and pore water pressure profiles in P38E

The evolution of the pore water pressure in borehole R55E, located 22 m from the PRACLAY gallery and drilled from the Connecting gallery, indicates that there has been an excess pore water pressure for several years, as can be seen in Figure 17. This means that the hydraulically affected zone due to heating extends more than 22 m from the PRACLAY gallery.

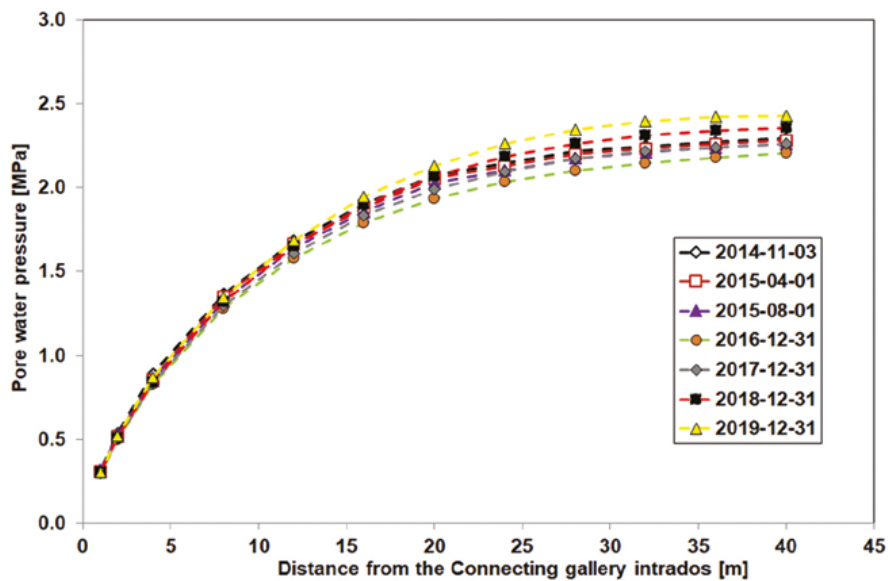


Figure 17 - Pore water pressure profiles in R55E

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 18, 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.

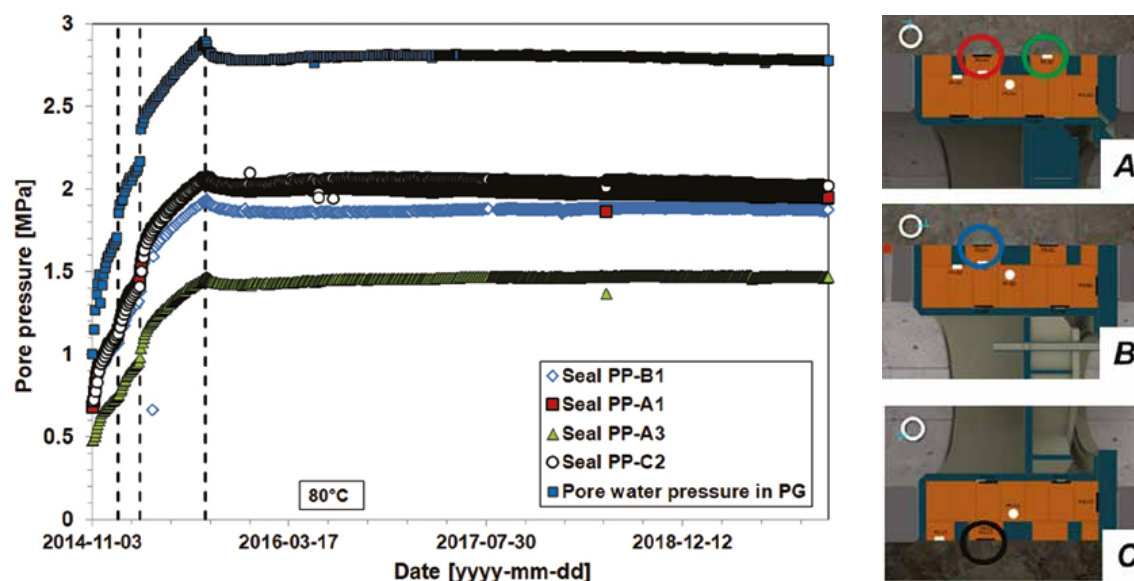


Figure 18 - Evolution of the pore water pressure at the Boom Clay/bentonite interface

In order to highlight the effect of the seal, Figure 19 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.

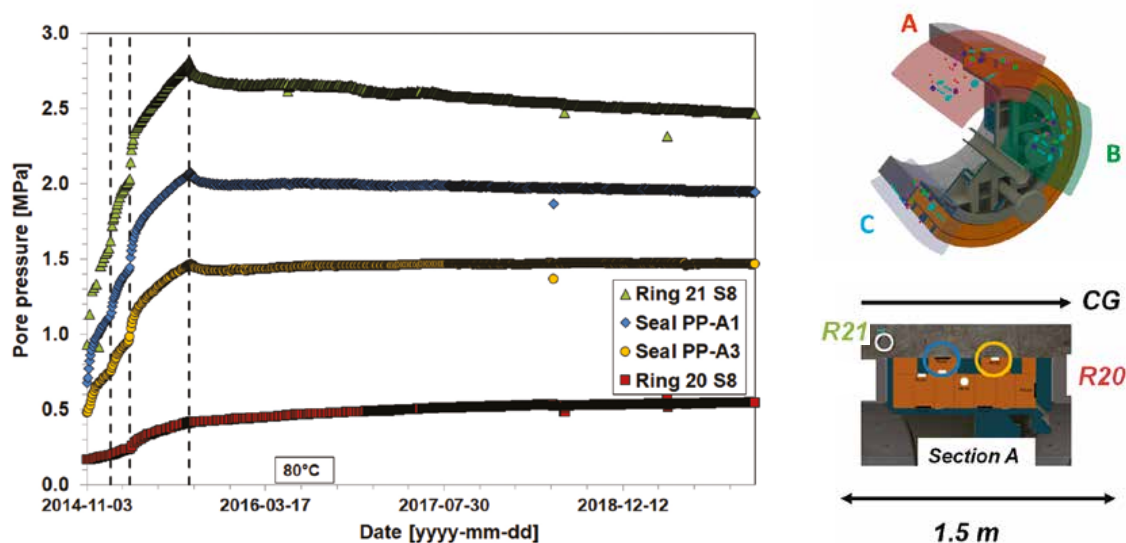


Figure 19 - Pore water pressure evolution at the Boom Clay/concrete lining and Boom Clay/bentonite interfaces

The evolution of the total pressure at the Boom Clay/bentonite interface can be seen in Figure 20. 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.

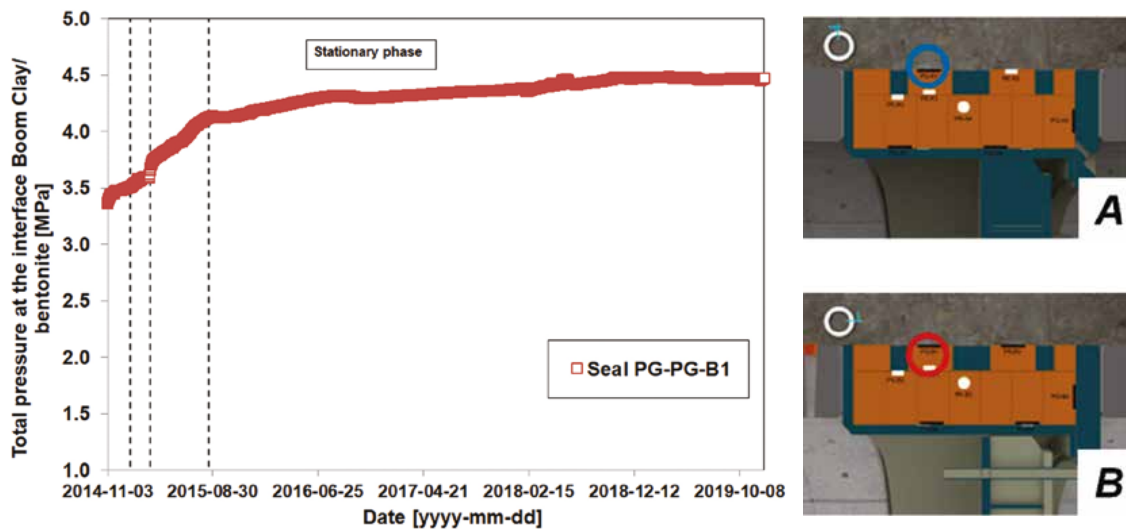


Figure 20 - Total pressure at the Boom Clay/bentonite interface in sections A and B

The movement of the seal structure towards the Connecting gallery was monitored by a total station and prisms attached to this structure, as can be seen in Figure 21. A significant increase in displacement during the start-up phase was observed and this has tended to be steady since the beginning of the stationary phase. The measured displacement remained quite constant and an average value of 12.5 mm over the three monitored prisms was observed at the end of 2019, without any effect on the stability and functioning of this seal structure.

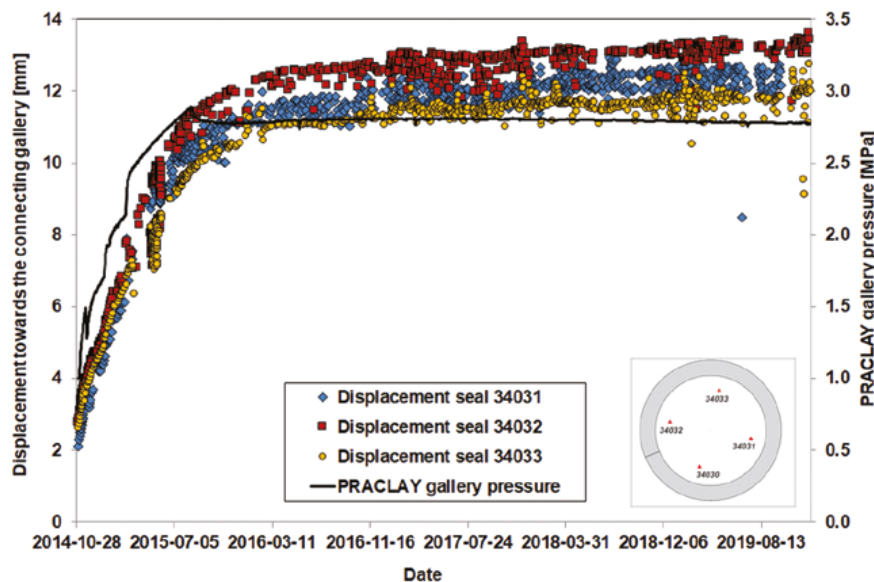


Figure 21 - Evolution of the movement of the seal structure towards the Connecting gallery since the beginning of the heating phase

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

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

The report entitled “In-situ hydraulic conductivity measurement for the Boom Clay around the Connecting gallery and PRACLAY gallery”, which summarises all the in-situ permeability test results for the Boom Clay around the Connecting gallery and the PRACLAY gallery obtained between 2010 and 2018, was finalised in 2019.

1.4. Improved interpretation of the test results by modelling

Continuous efforts were made during the previous years to improve the interpretation of the PRACLAY Heater test, which enables us to improve and confirm the THM characterisation of the Boom Clay. The measured temperature from the PRACLAY Heater test was interpreted first, because the temperature variation in the Boom Clay is dominated by heat conduction and because the hydro-mechanical coupling effect on heat transfer can be ignored. The interpretation of measured pore water pressure is more complex, because the thermal and mechanical coupling effect on the pore water pressure is strong.

IMPROVED INTERPRETATION OF THE MEASURED TEMPERATURE

Before the start of the PRACLAY Heater test, the small-scale ATLAS Heater tests were performed (ATLAS I, II, III & IV) between 1993 and 2012. These heater tests are performed to examine at different scales the THM responses to the heating of Boom Clay around disposal galleries for heat-emitting waste, and to confirm and/or refine the THM property values obtained from the laboratory characterisation programme, especially the cross-anisotropic thermal conductivity of Boom Clay. A lot of numerical modelling studies have been carried out to interpret the observed temperature evolution around both ATLAS and PRACLAY in-situ tests, and to determine if the measured temperature can well be reproduced using a single set of thermal conductivity values $\lambda_{\text{par}}/\lambda_{\text{per}}$ (parallel/perpendicular to the bedding) for the Boom Clay.

In the small-scale ATLAS Heater tests, an 8 meter long heater was installed in a small diameter horizontal borehole, at a distance of 11 m from the gallery lining. Sensors were installed in three horizontal and two inclined observation boreholes. With a simple geometry and simple boundary conditions, the ATLAS tests produced responses that depend mainly on Boom Clay properties. Three dimensional thermal modelling using cross-anisotropic thermal conductivity values for the Boom Clay, $\lambda_{\text{par}}/\lambda_{\text{per}} = 1.9/1.2$ W/m.K, provides results that closely agree with the measurements from all the temperature sensors (Figure 22).

In the large-scale PRACLAY Heater test, a 33 meter long heater was installed in a large diameter gallery, and the test conditions are much more complex than those of the ATLAS Heater tests. A large number of temperature sensors were installed in the mid-plane of the PRACLAY Heater test (i.e. the cross section perpendicular to the PRACLAY gallery axis at mid-length of the heated part), and the measured temperatures from these sensors were compared to results of a two dimensional plane model which is representative of the mid-plane. Computed temperatures match very well the in-situ measurements for all the temperatures in that plane when the set of thermal conductivity values derived from the ATLAS IV Heater test is used (Figure 23).

A full three dimensional thermal model with all components and materials of the setup was developed for the PRACLAY Heater test. Using the same set of thermal conductivity values derived from the ATLAS IV Heater test phase, local deviations up to 5 °C were observed when comparing the modelling results with the measurements from all the temperature sensors available around the PRACLAY gallery (not only those installed in the mid-plane). The three dimensional behavior of the complex test setup is being investigated further.

A report entitled “Three-dimensional thermal modelling of the PRACLAY Heater test” was finalised in 2019, and this report presents the mentioned numerical interpretation for measured temperatures from both the ATLAS IV and PRACLAY Heater tests.

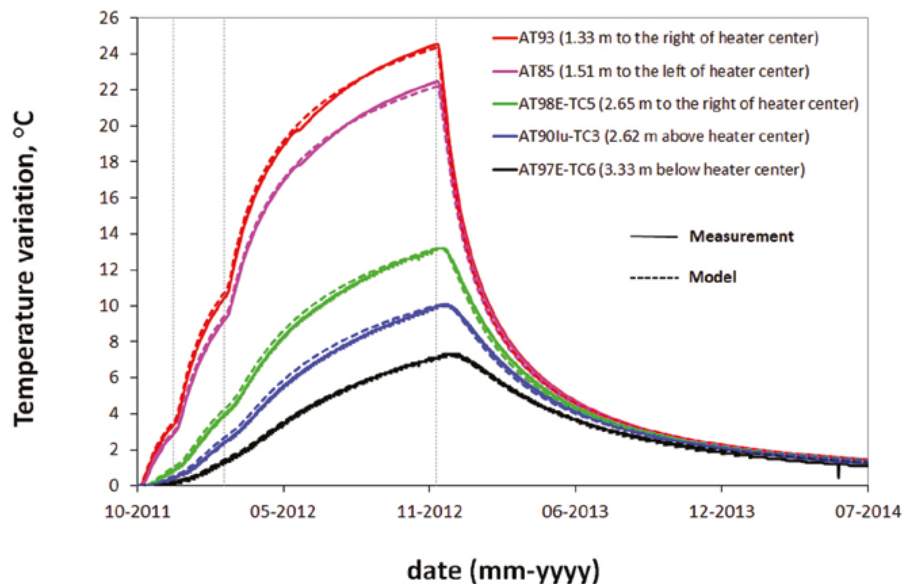


Figure 22 - Comparison between the modelled and measured temperature at five representative sensors in the ATLAS IV Heater test

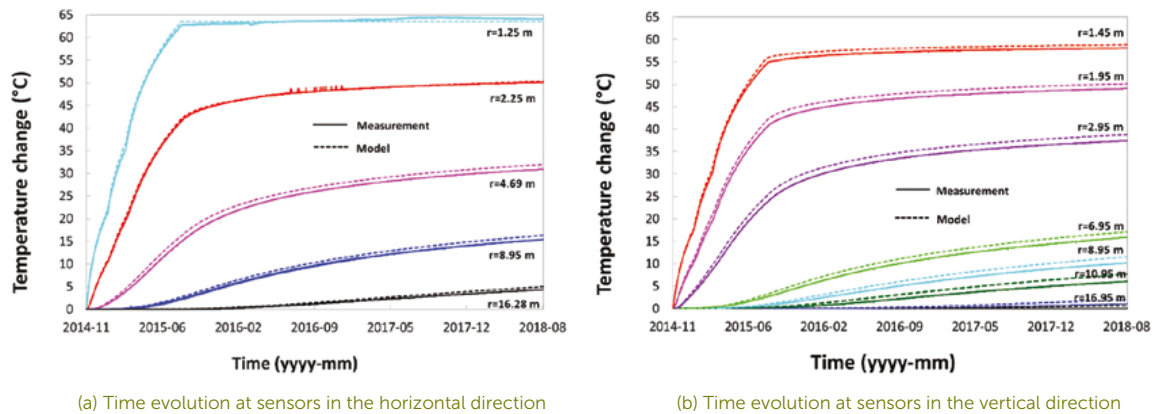


Figure 23 - Comparison between the measurement and modelling in the mid-plane of PRACLAY Heater test

IMPROVED INTERPRETATION OF THE MEASURED PORE WATER PRESSURE

Before the switch-on of the PRACLAY heater, a numerical prediction was made for the PRACLAY Heater test based on a two dimensional axisymmetric coupled thermo-hydro-mechanical (2D-Axis THM) model. The Heater test has been running for several years, and till now the predictive modelling results show a reasonably good agreement with the measured pore water pressure, which forms a solid basis for the further interpretation of the PRACLAY Heater test.

Based on the observations made during the first years of heating, the predictive 2D-Axis THM model for the PRACLAY Heater test was further updated and improved by

- using the improved Boom Clay thermal conductivity values, i.e. $\lambda_{\text{par}}/\lambda_{\text{per}} = 1.9/1.2 \text{ W/m}\cdot\text{K}$;
- improving the Drucker-Prager mechanical model for the Boom Clay used in the predictive model with minimum modification but representing the continuous alteration of the elastic modulus from the near-field to far-field Boom Clay in function of the strain level;
- by cross-checking the numerical interpretation of the PRACLAY Heater test with that of ATLAS IV Heater test.

The updated and improved 2D-Axis THM modelling results are extensively compared with the in-situ measurements during the first years of heating, based on which the improved THM characterization of Boom Clay is concluded.

In 2019, a report entitled “Two-dimensional coupled THM modelling of the PRACLAY Heater test: an interpretation after three years of stationary heating” was prepared. This report presents the numerical interpretation of the measured pore water pressure from the PRACLAY Heater test.

1.5. Mid-term evaluation of the PRACLAY Heater test

1. By the end of 2019, the PRACLAY Heater test had been running for more than five 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. total pressure sensors in the concrete lining blocks) or have delivered data with artefacts, thanks to the extensive network of instrumentation and the redundancy of critical sensors.
5. Generally speaking, the Boom Clay is behaving as expected. The observations from more than five 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:
 - In terms of temperature evolution, the improved interpretation of both the PRACLAY Heater test and the small-scale ATLAS IV heating test confirms that the heat transfer mechanism is by conduction. This has enabled us to refine our knowledge of the characteristics of this mechanism.
 - The clay seems to be able to withstand the thermal load without any drastic or sudden change in its hydro-mechanical properties and the structural integrity of the clay appears not to be affected by the thermal load. In fact, pore water pressure and temperature have evolved smoothly, which agrees well with numerical predictions using the continuum approach. Moreover, the evolution of the total pressure inside the clay has shown a similar increase as the pore water pressure, indicating that, during the heating phase, the effective stress in the clay around the heated gallery does not show any sharp variations and, in particular, any significant decrease that would mean a loss of contact between the clay particles, potentially leading to fracturing phenomena. Confirming this structural integrity under thermal stresses is one of the main objectives of the PRACLAY Heater test.
 - An extensive in-situ investigation of the intrinsic permeability showed that it did not change with the increase in temperature, confirming that the transport properties of the Boom Clay were not significantly altered during the experiment.

2. Supporting studies

2.1. Stability of the Connecting gallery

The strain inside the concrete segments and the convergence of the lining of the Connecting gallery have been monitored since the gallery was constructed in 2002. Figure 24 presents typical strain evolution in a concrete segment, in ring 30 (R30) near the PRACLAY gallery, which showed a continuous and slow evolution without any abrupt changes, except during excavation of the PRACLAY gallery. This indicates that the gallery lining is performing well. The effect of the start-up phase 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.

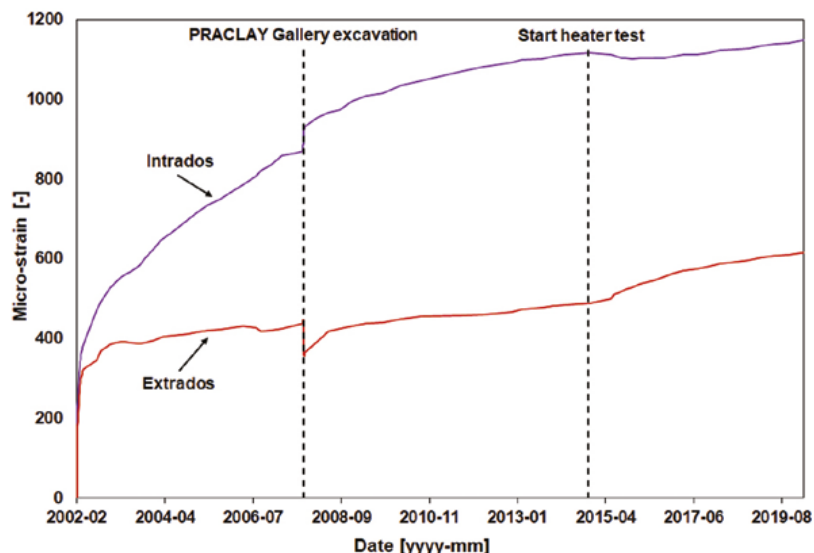


Figure 24 - Typical evolution of the strain in the segmental concrete lining (R30) of the Connecting gallery since the start of measurement

A few years ago (in 2012), a mechanical analysis of the Connecting gallery was started 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 design method, 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. As part of a general strategic review of the mechanical analysis of the stability of the Connecting gallery, EURIDICE will organise an internal workshop (SCK CEN, ONDRAF/NIRAS, EURIDICE) in May/June 2020. The goal of this workshop is to launch a new programme, including a theoretical and a monitoring part, to finally answer the remaining questions and to provide a clear understanding of the mechanical state of the Connecting gallery.

2.2. Micro-seismic monitoring programme

The micro-seismic system around the PRACLAY gallery consists of 23 transmitters and 19 receivers. It was installed in two phases between September 2006 (borehole sensors, Figure 25) and January 2008 (sensors in the gallery lining, Figure 26). The system has been operating continuously since 2006.

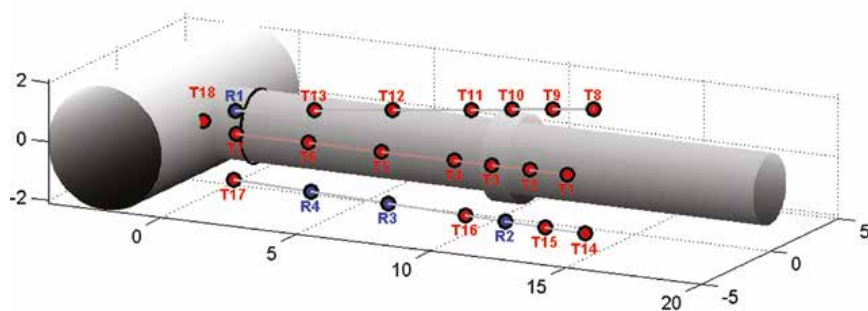


Figure 25 - [Red] transmitters (T) and [blue] receivers (R) installed in September 2006

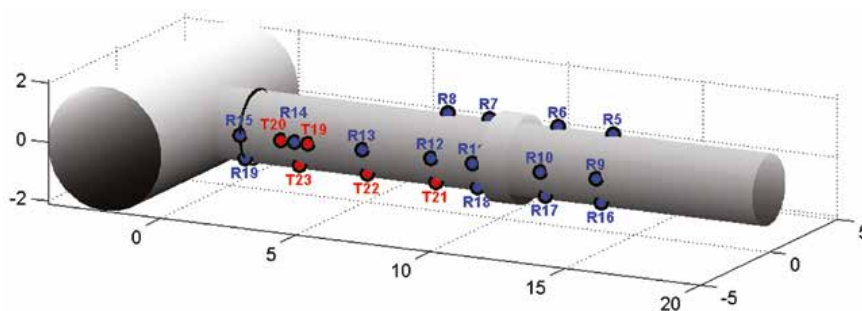


Figure 26 - [Red] transmitters (T) and [blue] receivers (R) installed in January 2008

The original objective of these micro-seismic measurements was to monitor the evolution of the host rock quality by measuring seismic velocity and damping over time, thereby assessing the influence of the different PRACLAY phases: from gallery excavation to heating.

An overall assessment of the quality of the data was made in 2017 after selecting relevant transmitter-receiver pairs. This assessment included a preliminary analysis of the waveforms and an estimation of some resulting geomechanical parameters of the surrounding host clay formation, based on the interpretation of the compressive (P) and shear (S) wave velocity.

Since the effect of the different phases, and in particular the heating phase, was not always unequivocally clear, EIG EURIDICE decided to opt for an independent analysis by the company GMuG, which had installed the set-up. This involved an assessment of the current state of the monitoring set-up, the selection of one transmitter-receiver pair with its related sensor data, and the application of signal processing techniques to this sensor data to extract the information available on the Boom Clay evolution.

Based on the complete sensor data set, GMuG first listed the sensors that were no longer functional. In January 2018 transmitters 01 to 05, 08, 14, 15 and 22 and receivers 05, 06, 09, 10 and 17 no longer functioned. Receivers located behind the seal are mostly gone; receiver 16 is left, but it is unreliable (switches on and off, for unknown reasons). Transmitters 01 - 05 failed first near the seal, then towards the Connecting gallery. Most of the transducers are not as sensitive as they were 10 years ago. To sum up, most of the sensors behind the seal (roughly between 10 and 15 m along the PRACLAY gallery axis in Figure 25 and Figure 26) were found to be no longer functional. In addition, the performance (such as the sensitivity and signal-to-noise ratio) of the remaining sensors had decreased gradually over time.

Several signal processing techniques were applied before the data was interpreted. These included signal stacking (up to one month), and low- and high-pass filters to remove high-frequency noise and DC offset (DC = direct current, or the constant, non-zero voltage signals), respectively.

The transmitter-receiver pair T2-R2 (see purple oval in Figure 25) was first selected to develop and test a methodology, as this pair had delivered the best-quality signals. The data from this pair was subsequently used for further quantitative analysis. After processing the signals, the travel times (and hence the velocities) of the seismic P- and S-waves could be determined. To obtain these travel times, manual "hand picking", assisted by cross-correlation when needed, was applied. The values obtained for these velocities were within the range of those previously observed in the field, such as around the second shaft or during the CLIPEX experiment (Mertens et al., 2004). The effects of the different events (such as excavation and heater switch-on) could be observed from the time evolution of the seismic velocities.

The sensor layout was designed before the cross-anisotropic character of the Boom Clay was fully considered. The measurements are therefore difficult to interpret in this context. The variability of the Boom Clay around the seal (with its large thermal and hydraulic gradients) is an additional complicating factor for the interpretation of the measurements. The exact value of the velocities also depends on accurate knowledge of the sensor positions, which have changed most probably due to the expected movement of the instrumented boreholes due to the PRACLAY gallery excavation.

Even with the selected pair T2-R2, which had delivered the best-quality signals, a lot of processing and assumptions were required to obtain the velocity values. Considering the lower signal quality of the other transmitter-receiver pairs, and due to the deteriorating performance of the sensors in general over time, it has been decided that no further effort will be expended to obtain new data. The current signals will be archived, and might still disclose information for the first years of PRACLAY. No further actions are planned for the micro-seismic monitoring programme.

The current sensor network will no longer be kept operational; instead it will be put in "sleep mode". The current hardware and software system for data collection (dating from 2006) would also need to be updated if there was ever a need to make it operational again.

2.3. Description of the HADES piezometers used for the study of in-situ Boom Clay pore water chemistry

As part of the R&D programme of ONDRAF/NIRAS on geological disposal in clay host rocks, the pore water chemistry of the Boom Clay has been studied for more than 30 years with the main objective being to better understand in-situ geochemical conditions of the clay, in both undisturbed and geochemically disturbed conditions. In-situ pore water extraction from the Boom Clay is carried out using piezometers that are installed in the Boom Clay host rock around the HADES URL.

EURIDICE contributed to a reference document describing twelve piezometers specifically used for Boom Clay pore water sampling in the HADES URL. The study included detailed research into historical documents and maps, a compilation of the most important piezometer data and an in-depth technical survey of the borehole drilling activities, construction and installation of these twelve piezometers.

Furthermore, for practical use, a HADES local reference coordination system, which is entirely based on the Belgian Lambert 72 geological reference system, was developed and described in detail. As a result of these combined research efforts to produce this report, the data in this report and its appendices represents the most accurate information available on the twelve piezometers.

2.4. PhD research

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

Since 2016 EURIDICE, together with SCK CEN's "Waste & Disposal" (W&D) expert group, has annually introduced one joint PhD research project within the PhD programme for Young Potentials at SCK CEN's Academy. Three were approved.

- 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 introduced 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 is funded through a European Erasmus Mundus Joint Doctorate Programme for the first three years (i.e. autumn 2017 to autumn 2020), and by SCK CEN for the final year (i.e. autumn 2020 to autumn 2021). This project was awarded to Ygee Larion.

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

This PhD research topic has direct relevance to concrete engineered barriers, which are an integral part of nuclear waste disposal concepts developed in Belgium. The PhD project is nearing its final year (2020). Year 3 was mainly devoted to developing a quantitative analytical framework to capture drying-shrinkage behaviour of hardened cement paste from a multiscale point of view. Extensive use was made of the work completed in the first two years of the PhD: (i) a multiscale pore network model for simulating water sorption isotherms (see Figure 27) and (ii) analytical homogenisation for estimating effective bulk modulus of the material. Throughout the PhD, the central idea has always been to make the transition from mere knowledge of ordinary Portland cement composition and existing microstructural understanding of the material towards predicting required material properties. In other words, the focus is on a predictive modelling approach without the need for too many experiments.

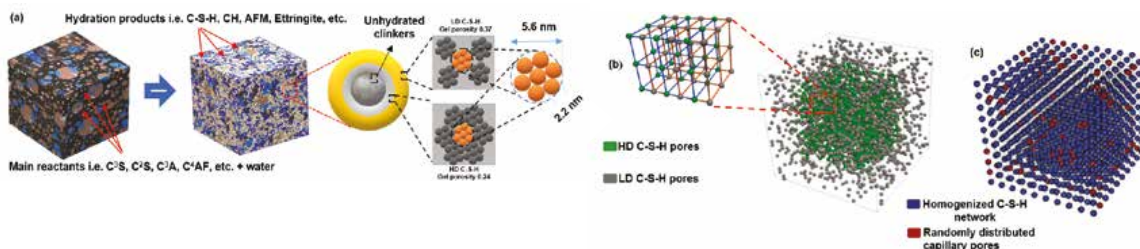


Figure 27 - A pore network generated from microstructure of cementitious material: (a) generating microstructure from chemical composition of cement and its phase fraction distribution, (b) generating hierarchical networks and homogenising them, (c) final homogenised network including a wide pore size range.

The following milestones were achieved in 2019: (i) a journal paper on pore network modelling and its application for water sorption isotherms was published in Cement and Concrete Composites (<https://doi.org/10.1016/j.cemconcomp.2019.103415>); (ii) a Waste & Disposal talk was given at SCK CEN on 13 June; (iii) a poster was presented at SCK CEN's PhD Day on 2 October: "A Multiscale Framework for Drying Shrinkage Strains from Cement Formulation"; (iv) an extensive study on the permeability of cementitious materials was initiated and a firm foundation has been laid to exploit the power of pore network modelling, which will be continued in the early part of 2020.

The final year will focus on completing the modelling work for estimating intrinsic and relative permeability of hardened cement paste using pore network modelling, followed by continuum scale modelling of coupled thermo-hydro-mechanical behaviour of a concrete engineered barrier.

2.4.2. 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 launched by EURIDICE, SCK CEN's W&D and ONDRAF/NIRAS. This project is co-funded by ONDRAF/NIRAS and SCK CEN and is a joint collaboration with Laboratoire Navier/CERMES, l'École des Ponts ParisTech. 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 problems 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 objective of this PhD thesis is therefore to improve our understanding of the long-term behaviour of the Boom Clay based on a thorough literature review, with a new experimental programme including both laboratory and in-situ tests in HADES to develop a relevant constitutive law and numerical modelling. The PhD started in October 2018 and the first year was devoted to the literature review, and to establishing and starting a new experimental programme.

After having studied the main characteristics of the microstructure and the mineralogy of the Boom Clay, the literature review focused on experimental creep work to study its volumetric, shearing and anisotropic behaviour. Previous studies showed that compressibility behaviour was analysed using unloading/reloading loops during oedometric tests at low and high pressures. These types of tests determined many parameters for the Boom Clay, such as compressibility parameters, secondary deformation coefficient and pre-consolidation stress, which are essential for understanding its mechanical and chemical creep behaviour. In addition, the literature review showed that the shear behaviour of the Boom Clay had been studied using triaxial tests under different experimental conditions. This research indicated that creep was more significant when deviator stress was high and that there was a creep threshold under which creep deformation cannot be found. It was also pointed out that even the temperature range and loading rate can affect the creep deformation response. Furthermore, anisotropic behaviour was investigated using oedometric tests in different directions with respect to the bedding plane. Regarding the modelling review, general research was performed on the elasto-visco-plastic behaviour of the Boom Clay by collecting different existing constitutive laws.

Based on this in-depth review, a new laboratory experimental programme was developed to study the time-dependent behaviour of the Boom Clay using oedometer and triaxial tests. First, the drill core was sampled and an identification test was carried out on the sample to be tested. The basic geotechnical properties, such as water content and bulk density, were determined. Then, low-pressure (from 0.05 to 3.2 MPa) and high-pressure (from 0.125 to 32 MPa) oedometric creep tests were performed by applying loading-unloading cycles with different constant levels of stresses. In addition to multiple stage loading oedometer creep tests, other oedometer tests will be performed at different deformation rates using a press. Furthermore, using triaxial tests under drained conditions, creep will be investigated under different deviator stresses. In both oedometric and triaxial tests, the relationship between microstructure and creep behaviour will be explored using Mercury Intrusion Porosimetry (MIP). Table summarises the experiments already conducted and the experiments still to be done on old (2007) and new (2016) damaged and undamaged Boom Clay samples.

Experimental programme

		Oedometer tests				Triaxial tests	
		Different stress levels		Different constant strain rates		Different deviatoric stresses	
		Low pressure	High pressure	Range of ϵ		Range of q	
		0.05-3.2 MPa	0.125-32 MPa	Low to prevent pore water pressure generation		Low for creep threshold	High for tertiary creep
BOOM CLAY	Old samples	X	X	0	0	0	0
	Undamaged samples	X	0	0	0	0	0
	Damaged sample	0	0	0	0	0	0

Table 1 - Description of the experimental programme

As an example, Figure 28 presents the results of a low-pressure oedometric test on a Boom Clay sample from borehole CG78-79W. The saturation process of the sample was performed under in-situ effective stress conditions to minimise microstructural change. Point B corresponds to the saturation stage before beginning the unloading/loading cycle. The end of this process is marked by point C, characterised by a higher void ratio, which meant that even under in-situ effective stress conditions the sample swelled during this process. This might prompt questions concerning the representativeness of the test, as swelling modifies the microstructure of the clay. Further analysis is needed to supplement this information.

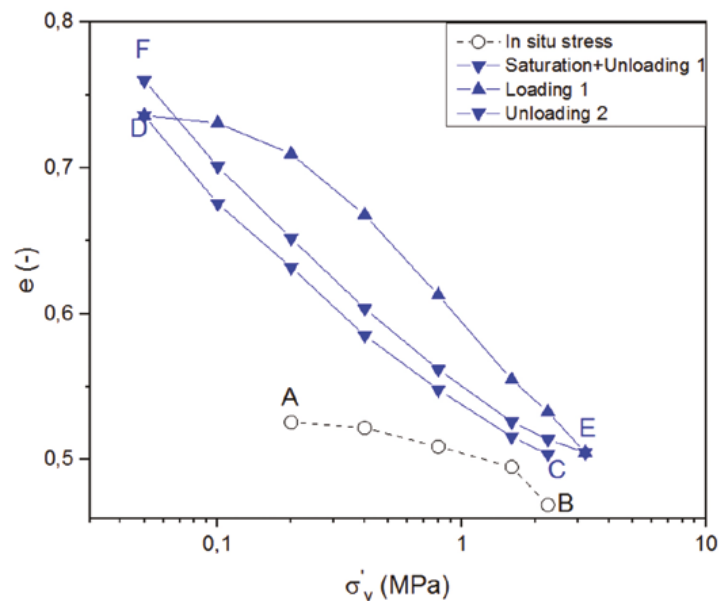


Figure 28 - Loading/unloading curves obtained during a low-pressure oedometer test. Path A to B brings the sample to the in-situ effective conditions. Path B to C indicates the saturation process with the presence of a small amount of swelling. Path C to D to E to F shows the unloading/loading process for the characterisation of the volumetric behaviour of the clay.

2.4.3. 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 are dealing with complex THM coupling problems, and their inverse analysis based on numerical modelling is quite time-consuming. The ROM technique can enable us to perform inverse modelling for parameter estimation as well as uncertainty analysis at a reasonable 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.

So far, the PhD researcher has (i) applied the snapshot-based ROM technique to the coupled THM problem, (2) devised adaptive strategies that optimally select snapshots and generate a certified reduced basis, (3) developed an a posteriori error estimator for a basis generation and certification of the problem, and (4) efficiently implemented the developed ROM technique in MATLAB. The next step will be to use the current technique for the inverse analysis of the ATLAS and PRACLAY heater tests.

2.5. Core Management & 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 29).



Figure 29 - 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.

The core management workflow in GSIS was successfully tested in 2018 during the sampling campaign for a selected core request, and further implemented in 2019. 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.

In 2019 a major update of the GSIS interface was completed, focusing on the following issues:

- Supporting the 3D view of the database objects
- Changing privilege management and visibility of data

The 3D view of the database objects is implemented for all database objects (regional boreholes, surface objects and HADES URL objects), but is mainly useful for the latter category. The complex geometries and spatial relationships around the HADES URL are best visualised using a 3D view, now accessible to all GSIS users. A 3D view can visualise objects grouped in user-defined selections, whereby the view angle and zoom can be interactively changed. The feature also supports on-click information and links to the visualised objects. The 3D scene can be saved to a kml file for viewing in another application.

3. Instrumentation & Monitoring

Work in 2019 on instrumentation and monitoring involved the in-depth research on sensor performance as well as operational aspects. In the context of the development of the HADES inventory (which is also related to the IAEA Compendium), input has been given on the sensors and other monitoring equipment that has been deployed in HADES throughout the different experimental setups.

Since construction work on HADES began in the early 1980s, many experimental setups 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, dealt with the performance assessment of the instrumentation installed as part of the CLIPEX project. The final version of the CLIPEX sensor performance study was published in 2018. Based on this study, a paper is currently being developed.

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 CLIPEX experimental set-up: by assessing the measurement performance of each individual sensor, the success factors for a monitoring set-up (sensor technology used, installation, sensor environment, accuracy and representativeness) can be derived.

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 1200+ sensors were grouped into 32 "sensor sets", each containing similar sensors (same technology) installed in similar conditions.

Assessment involves checking each individual sensor against a number of criteria. The five main categories of criteria that were defined for the first study (assessment of the CLIPEX test) have been applied again. These are installation, operation of the sensor, environment, signal quality and sensor characteristics. The criteria in the "installation" category include the date of installation or the availability of formal installation procedures. The "environment" category specifies the host medium of the sensor, the temperature to which the sensor is exposed, etc. The "sensor characteristics" category includes calibration parameters (making it possible to derive long-term drift) for the accessible sensors (more specifically, pressure transmitters). The assessments are summarised in spreadsheet tables (one for each sensor set). The contextual information and the conclusions are recorded in the corresponding assessment section of the report.

The first draft was discussed with ONDRAF/NIRAS at the beginning of 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.

Operational work involved mainly calibration of de pressure transmitters of the PRACLAY set-up. A total of 29 multi-filter piezometers, involving several hundreds of transmitters, were calibrated. The calibration work not only allowed to maintain the accuracy of transmitters, it also delivers a lot of data that can be used for the assessment of the long-term performance for these sensors. Finally, the calibrations also give input to review and improve the calibration process itself, from operation to interpretation and application of the results.

First initiatives were further taken for a complete and well-organised inventory of the sensors and other measuring equipment, in the context of the migration to the LabTool platform. Also all the measurement data linked to the sensors, of which some have not yet been stored in a formal database, will be brought together on this platform. This action fits in the more global action on a complete scientific and technical inventory of the URL HADES, which will be implemented from 2020 on.

4. Participation in international research projects

4.1. EC Modern2020

As part of the Horizon 2020 Euratom Work Programme NFRP6-2014 “Supporting the implementation of the first-of-the-kind geological repositories”, a project called “Modern2020” was approved by the European Commission (EC) in early 2015. The objectives were to investigate monitoring strategies, technologies, demonstrations and stakeholder interaction in the context of geological radioactive waste repositories. The project started on 1 June 2015 and ended on 31 May 2019. The project consortium consisted of 28 partners from 12 countries.

In the project summary of the Modern2020 project, the general objective was stated as follows: *“The Modern2020 project aims at providing the means for developing and implementing an effective and efficient repository operational monitoring programme, taking into account the requirements of specific national programmes.”*

The project consisted of four technical work packages (WPs), two of which involved EURIDICE: WP3 (Monitoring Technology) as coordinator/advisor and WP4 (Demonstration and Practical Implementation) as Work Package Leader. The other two WPs are Strategy (WP2) and Societal Concerns and Stakeholder Involvement (WP5). The activities regarding the dissemination of the results were grouped under WP6, where EURIDICE participated in two main activities.

The work on WP3 was already completed in 2018. Some final reporting contributions were delivered to the task leader responsible for wireless monitoring (NRG).

The main work in 2019 was devoted to WP4, in which EURIDICE is the Work Package Leader. WP4 brings together demonstrator set-ups that are being developed and are or will be operated in foreign URLs: Finland (Olkiluoto), France (Bure and Tournemire) and Switzerland (Mont Terri). In addition, this WP also revisits some existing cases, which were re-assessed with the focus on monitoring experience that is relevant for repository operation, such as the use of monitoring data for decision-making, or the involvement of local stakeholders in the field set-up. With the project ending in 2019, most of the work focused on accomplishing the five project deliverables (D4.1 to D4.5) of WP4 (coordinated by EURIDICE). Four of these reported on the field demonstrators; reporting was carried out by the respective task leaders (POSIVA for the “EBS Monitoring Plan” in D4.1, ANDRA for the “AHA” demonstrators in the Bure URL in D4.2, IRSN for the LTRBM demonstrator at the Tournemire URL in D4.3, and NAGRA reported in D4.4 on the FE in Mont Terri and the TEM in the Grimsel facility). EURIDICE summarised the results, adding those from other demonstrators into the final deliverable D4.5 for WP4.

EURIDICE contributed to two main project activities that were organised in 2019. In April 2019 it presented the preliminary results from the demonstrators at the Modern2020 International Conference (Paris). It also took part in the Monitoring School, which was held at the Äspö facility near Oskarshamn (Sweden), giving a lecture on monitoring aspects in demonstrator set-ups, and also organising a practical exercise on the installation, data collection and interpretation (strain gauges in a concrete sample).

Final approval of the Modern2020 project deliverables was obtained from the EC in December 2019.

4.2. European Joint Programme on Radioactive Waste Management and Disposal – 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.

As per the schedule, EURIDICE delivered its contribution for Task 1.2 with the “State-of-the-art report on the THM behaviour of Boom Clay” in mid-December 2019.

For Task 2.3, EURIDICE will provide experimental data on the large-scale in-situ PRACLAY Heater test running in the Belgian HADES URL for the Benchmark exercise. This Benchmark has been defined and

documented in terms of geometry, materials (and their main THM parameters), THM boundary conditions, output requirements, etc. Different modelling scenarios were proposed to enable the partners to carry out the Benchmark exercise step by step. This Benchmark proposal was discussed with ANDRA and NAGRA in a working meeting on 29 November 2019 in Paris.

Additionally, in December 2019, EURIDICE delivered its contribution to the first Interim Progress Report (Description of the work done during the period from June to November 2019), as well as the AWP2 (Annual Work Plan for Year 2) covering the period from June 2020 to May 2021.

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 group with the following activities:

- arranging and analysing a survey of the coordinates of the casing entrances;
- setting up the data acquisition system;
- checking the filter coordinates;
- closely monitoring sampling from 27 filters;
- designing and installing the experimental set-up;
- calibrating the pore water pressure transmitters;
- characterising the hydraulic conductivity of the Boom Clay in the area of the gas test;
- discussing the interpretation of the HTO migration test;
- reviewing the progress reports.

4.3. 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 draft report on the "Investigations, experiments and demonstrations carried out in Belgian URF HADES" was compiled in 2019. The report covers the following aspects:

- A general description of the HADES URF.
- Former roles played by the HADES URF and future goals.
- Design of the HADES URF.
- Key phases of HADES URF 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 finalise the Compendium in September 2020 and publish it in 2021.

Training

In March 2019 the IAEA invited EIG EURIDICE to take part in a workshop on "Planning URF experiments" in China. The workshop was requested by the Beijing Research Institute of Uranium Geology (BRIUG), which planned to start constructing its URF in Beishan in 2019. The aim was to help BRIUG define a hydro-

mechanical characterisation programme of the crystalline host rock. The workshop was organised by the IAEA together with three experts, from NAGRA (Switzerland), NWMO (Canada) and EURIDICE (Belgium). Guangjing Chen, as a representative of EURIDICE, gave three presentations about (i) the construction history of the HADES URL, (ii) the characterisation of the Boom Clay hydro-mechanical behaviour and (iii) the numerical simulations supporting the RD&D programme of a URL.

4.4. FPS Economy funding scheme for improvement of radiation and nuclear safety in Eastern Europe

As part of the Federal Public Service (FPS) Economy's funding scheme for improvement of radiation and nuclear safety in Eastern Europe, EURIDICE welcomed Slovak experts in June 2019. During the technical visit, they discussed THMC research in the Belgian and Slovak programmes. EURIDICE also gave the experts a guided tour of the permanent exhibition and the HADES URL.

In November 2019 Guangjing Chen from EIG EURIDICE delivered a training course on finite element THM code Code_Bright at the Technical University of Slovakia. The participants came from various institutions involved in the geological disposal of radioactive waste in Slovakia and the Czech Republic. Code_Bright was developed by the Universitat Politècnica de Catalunya (BarcelonaTech, UPC), and is being increasingly widely used in the HLW geological disposal community (Spain, Sweden, France, Switzerland, Canada, Finland, Belgium, USA, etc.).

4.5. JRC-Geel

Since 1999 EIG EURIDICE has delivered services for JRC-Geel's long-standing operation of an ultra-low-level radioactivity laboratory in support of European Commission policies in fields such as international standardisation, radioactive waste management and radioprotection. Some key projects in 2019 included: characterisation of reference materials for food safety and nuclear decommissioning, and radiotracer studies of water from the Pacific Ocean to determine the transport of iron from hydrothermal vents, which contributes significantly to the ocean's ability to bind CO₂, and support to international research groups performing studies. A new field of research concerns natural archives. In 2019 samples were analysed from Greenland ice cores and corals from both tropical waters and cold water. The latter projects were carried out within JRC-Geel's external access programme and aim at improving our understanding of past natural and anthropogenic events. This can in turn improve our understanding of processes involved in climate change. JRC-Geel has collaborated with some of the biggest experiments in the world aiming at detecting neutrinos from the sun and the double beta decay in ⁷⁶Ge. The results from the GERDA experiment were recently published in a high-profile article in Nature. The data refutes all former claims at the detection of the neutrinoless double beta decay in ⁷⁶Ge and marks the way forward for future experiments. The GERDA detector is located in Gran Sasso in Italy, but all the circa 40 germanium crystals that make up the central core of the experiment have been tested in HADES.

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

4.6. Max Planck Institute – the LEGEND project

Unravelling the mystery of so-called neutrino particle properties (mass, nature, interactions) is one of the main focal points of fundamental particle physics research in the 21st century. The international LEGEND (Large Enriched Ge Experiment for Neutrinoless double beta Decay) partnership 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 in Italy, starting in 2021. Part of these detectors were tested in the HADES URL.

The first batch of four detectors was produced by MIRION – Olen in October 2019 and subsequently delivered to the HADES underground laboratory. After a commissioning phase underground in mid-2019, a one-month characterisation campaign took place specifically in HADES to prevent the cosmic ray activation of the detectors and lower background contribution. The measurements were prepared and conducted by LEGEND collaborators, including PhD students and the JRC-Geel group of Mikael Hult,

with the support of the EIG EURIDICE team. Using artificial radioactive sources (^{60}Co , ^{228}Th and ^{241}Am) mounted in custom-designed holders on a static and scanning tables, the main properties of the four detectors were extracted, i.e. their nominal operational voltage, energy resolution, background rejection capabilities and active volume. These parameters will be useful for the subsequent LEGEND experiment and the interpretation of the results.

The collaboration between LEGEND and EIG EURIDICE will continue in 2020 with the delivery of additional Ge detectors.

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

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

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

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

In 2019 EURIDICE's work focused on the thermal-hydro-mechanical 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 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 clay 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 the heat.

The numerical model was developed using the finite element software COMSOL Multiphysics® and focused on poorly indurated clays by simulating the effect of the heat in 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 -4 (UOX of different lengths) and SC-5 (MOX).

The finite element simulations were performed in 2018-2019 and the report is being finalised for delivery in January 2020. An example of the results of such a simulation can be seen in the next two Figures, which show the distribution of the temperature at different times (Figure 30) and the temperature and pore water pressure evolution and the stress path at the wall of the excavation (Figure 31).

The temperature distribution at different times presented in Figure 30 shows that the temperature increased quickly around the disposal gallery before rising slowly into the clay as heat spreads across the far field. The distance between the disposal galleries was sufficient to avoid mutual interaction, i.e. the temperature evolution around one gallery does not affect the peak temperature of its neighbour. The effect of neighbouring galleries was taken into account by imposing adiabatic boundary conditions along the vertical edges of the model. A maximum of 60°C was reached at the excavation wall within the two first decades, after which the temperature gradually decreases, as seen in Figure 31 (a). At the same location, the pore water pressure increases because of the significant discrepancy between the thermal expansion coefficient of the solid phase and that of the liquid phase (Figure 31 (a)). The pore water pressure rose quickly to a value close to the undisturbed value of the pore water pressure, equal to 4 MPa in this case (repository at a depth of 400 m).

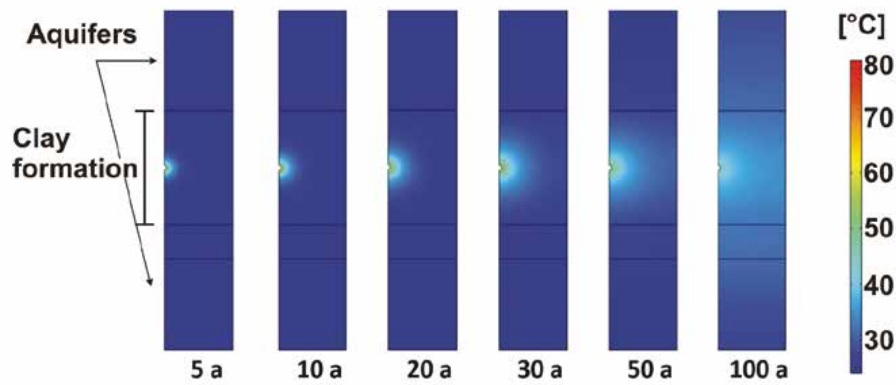


Figure 30 - Distribution of the temperature around one disposal gallery at several time intervals dating from disposal (after 5 years, 10 years, 20 years, 30 years, 50 years and 100 years).

The analysis of the variation in the mechanical state of stress is shown in Figure 31 (b), from the gallery excavation phase to the thermal phase. It can be seen that the excavation process generates plastic strain, which is consistent with the excavation-damaged zone (EDZ) observed during the excavation of the Connecting gallery in the HADES URL. The variation in temperature affects the mechanical state of stress by accumulating additional plastic strain around the gallery. This additional irreversible strain might be expected to modify the EDZ by extending the initial cracks, increasing the permeability or generating irreversible changes in the EDZ, affecting the favourable properties of the clay. Experimentally, the combined effects of a thermo-hydro-mechanical loading are studied through the ongoing large-scale PRACLAY Heater test. The in-situ measurements of the permeability around the PRACLAY gallery during the stationary phase of the experiment showed that there are no modifications of the intrinsic permeability, meaning that the clay has not lost its favourable properties up to now.

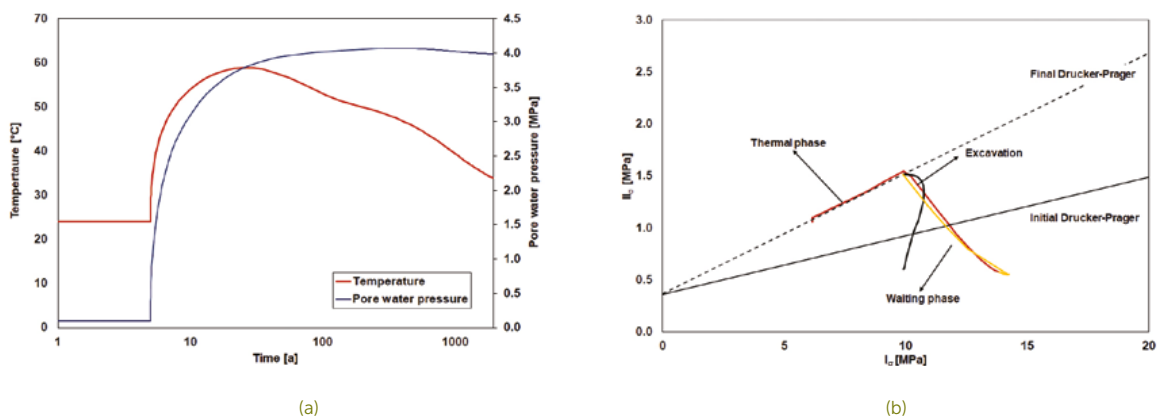


Figure 31 - (a) Pore water pressure and temperature evolution at the gallery wall obtained from a numerical analysis of a geological disposal facility. (b) Stress path in the plane of the first invariant of the effective stress tensor and the second invariant of the deviatoric effective stress tensor for a point at the gallery wall

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

As manager and operator of the HADES URL, EIG EURIDICE supports ONDRAF/NIRAS and its research partners by providing samples, data and expertise for studies carried out in collaboration with third parties in various scientific fields of importance for geological disposal in clay. Typical research topics include the characterisation of the components of the Boom Clay, its pore structure, pore water chemistry, solute, gas and heat transfer mechanisms, microbial activity within and around underground structures, etc. EURIDICE is in charge of the daily management, follow-up, scientific operation and reporting of the long-term, large-scale PRACLAY Heater test.

In addition, EIG EURIDICE supports ONDRAF/NIRAS by writing topical documents on specific aspects of the geomechanical behaviour of the Boom Clay. Scientific publications and reports, such as state-of-the-art reports on the properties of clays and their mechanical, hydraulic and thermal behaviour, based on studies carried out by EURIDICE and its partners or the scientific interpretation of the long-term, large-scale PRACLAY Heater test, constitute significant inputs to the Safety and Feasibility Case of ONDRAF/NIRAS, planned for 2022.

RD&D Part 2

The surface disposal programme for category A waste - cAt Project



Introduction

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

An important step in the successful completion of this project 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 on the surface disposal facility 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 of the planned disposal facility;
- Calculations and validation tests of the hydrogeological models used in the licence application for the planned disposal facility;
- Preparation and instrumentation of the planned test cover;
- Instrumentation of the demonstration test for construction of concrete modules.

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

In 2019 EIG EURIDICE's support was sought in carrying out additional long-term studies over the next few years. In particular, a systematic performance analysis for the containment capability of the disposal system was initiated. Models were developed to assess both expected performance and robustness in the event of any disruption to the system's functioning. The results have been partially reported, and additional work will be undertaken in 2020 to further substantiate the containment performance of the disposal system.

Hydrogeological models

Point dilution tests were performed last year on a seasonal basis (Figure 32). Interpretation and reporting were finalised ("Hydrogeological investigations for validation of groundwater flow directions and velocities at the category A site", NIRON-TR 2019-17). The final test results confirm the fluxes that were calculated previously. Groundwater levels are still measured on a monthly basis: this information is needed to determine the gradient of the water table in the vicinity of the disposal site.



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

Two large-scale pumping tests were organised towards the end of 2018 in order to confirm the hydraulic permeability of the upper aquifer. These were reported in “Boorputten en pompproeven op de bergingsite cAt” (NIROND-TR 2019-08) and in “Interpretation of pumping tests performed at the cAt site” (NIROND-TR 2019-06). The upper aquifer is locally (at and around the disposal site) characterised by a coarser facies in the Upper Mol sands, and this is confirmed by the tests. Horizontal hydraulic conductivity is in this particular layer about four times larger compared with Upper Mol and Lower Mol sands.

Due to drainage and re-injection activities at FBFC International, which affected the water table and movement up to the western tumulus location, it was not possible to validate the local hydrogeological model and the derived geo-transfer factor (GTF) for that disposal unit. In the safety report, only a GTF for the eastern tumulus is provided. FANC asked for a site-specific hydrogeological and transport model with emphasis on the western tumulus situation and on the occurrence of wetlands between the disposal site and the Witte Nete river in the north. SCK CEN started work on a conceptual hydrogeological model that was discussed in November 2019 with FANC, in order to obtain the go-ahead. This meeting initiated the start of the modelling exercise, which should be finalised by mid-2020.

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 2020 in order to start the construction phase of the test cover in 2021.

Demonstration test

In order to assess the technical feasibility of the module construction techniques and the industrial feasibility of the concrete that has been optimised for long-term safety and has been tested on a laboratory scale, a demonstration module construction test for the cAt project has been underway since 2011 (Figure 33).



Figure 33 - 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 2019. Some data collection and analysis continued, however.

Operation and safety of installations



General

The Statutory Rules define the responsibilities and tasks of EIG EURIDICE concerning the management and operation of the installations on the land for which EIG EURIDICE holds a building lease. In 2019 these tasks were performed in accordance with applicable regulations, ensuring safe operations.

Under the agreement between EURIDICE, SCK CEN and ONDRAF/NIRAS on safety and well-being at work, which defines the safety structure of EIG EURIDICE, monthly meetings were organised between representatives from the three parties. These meetings mainly focused on the action points from the JAP (JaarActiePlan): prevention policy, fire safety, the electrical installations, hazardous products and shaft 1 refurbishment.

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

- Connection of monitoring devices to the data-logging system in HADES;
- Technical support to the PRACLAY Seal and Heater tests;
- Technical support to the EURAD-GAS in-situ experiment;
- Sampling campaigns on core samples;
- Operation of the hoisting system and technical assistance during visits.

With respect to safety, two new presentations were made:

- Safety presentation for external companies working on the EURIDICE site;
- Safety presentation for visitors to HADES.

A full risk analysis of the electrical installations on the EURIDICE site was completed in 2019. Actions are being defined and detailed for the refurbishment of the electrical installations, to be completed by the end of 2020.

Monthly work lunches on safety issues were organised with all EURIDICE staff.

A reporting system was launched in order to allow everybody to report any unsafe situation at EURIDICE.

Underground installations and associated hoisting systems

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

With the ONDRAF/NIRAS financing agreement covering the period 2016-2020, a budget for the refurbishment of the shaft 1 hoisting system has been put in place. After project preparations in 2016 and the appointment of an engineering company in 2017, the project work in 2018 successfully addressed the topics shaft stability study, identification of the regulatory requirements and specifications for the design and build phase. 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. The project kick-off meeting was organised in September 2019, followed by planning, safety and design meetings. The work on site will start in early 2020, with the aim of commissioning the new hoisting system by the end of 2020. During the on-site work no visitors will be allowed in the HADES URL.

The watertight bitumen layer between the inner and outer concrete rings of shaft 2 was topped up (approx. 5m³) to prevent corrosion of its steel protective ring.

Preparations were made and a contract was awarded for the installation of two fireproof doors in the underground laboratory, following a recommendation in the 2016 fire risk assessment report for the EURIDICE site. They are scheduled to be installed in January 2020.

Above-ground installations and buildings

The operations team carried out standard maintenance and necessary repairs on the installations, buildings and infrastructure in 2019.

Following the signing of the Green Deal statement of intent in 2018, a management plan on biodiversity was delivered by Biotoop in February 2019 and a public tender was launched for the implementation of this plan. Following negotiations, the company Natuurwerk was awarded the contract and will start work in the spring of 2020. EURIDICE will take care of the periodic maintenance of the vegetation. The accomplishment of this project will be a win-win situation for nature and for our employees and visitors. A richer biodiversity on and around the EURIDICE site will improve everyone's health and well-being.

In accordance with the SCK CEN system, a new fire alarm system has been designed and installed in the above-ground buildings of EURIDICE. The system will alert staff to an emergency so that they can take action to protect themselves, the general public, the installations and the buildings. The installation of this new system with smoke detectors, fire alarm buttons and sirens was one of the recommendations of the fire risk assessment in 2016.

Licences

The **operating licence** is valid until 2024. However, due to important changes to the infrastructure (shaft 1 renovation project), a new operating licence will be required. Meetings with the Federal Public Service for Employment, Labour and Social Dialogue and the community of Mol regarding the application for a new licence have taken place and the application will be submitted in the second half of 2020.

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

The **environmental licence** of EIG EURIDICE (granted in November 2013) has been renewed. An update was requested when applying for the environmental permit needed for the shaft 1 renovation project. The new licence was granted on 8 August 2019 and is valid until 30 October 2033.

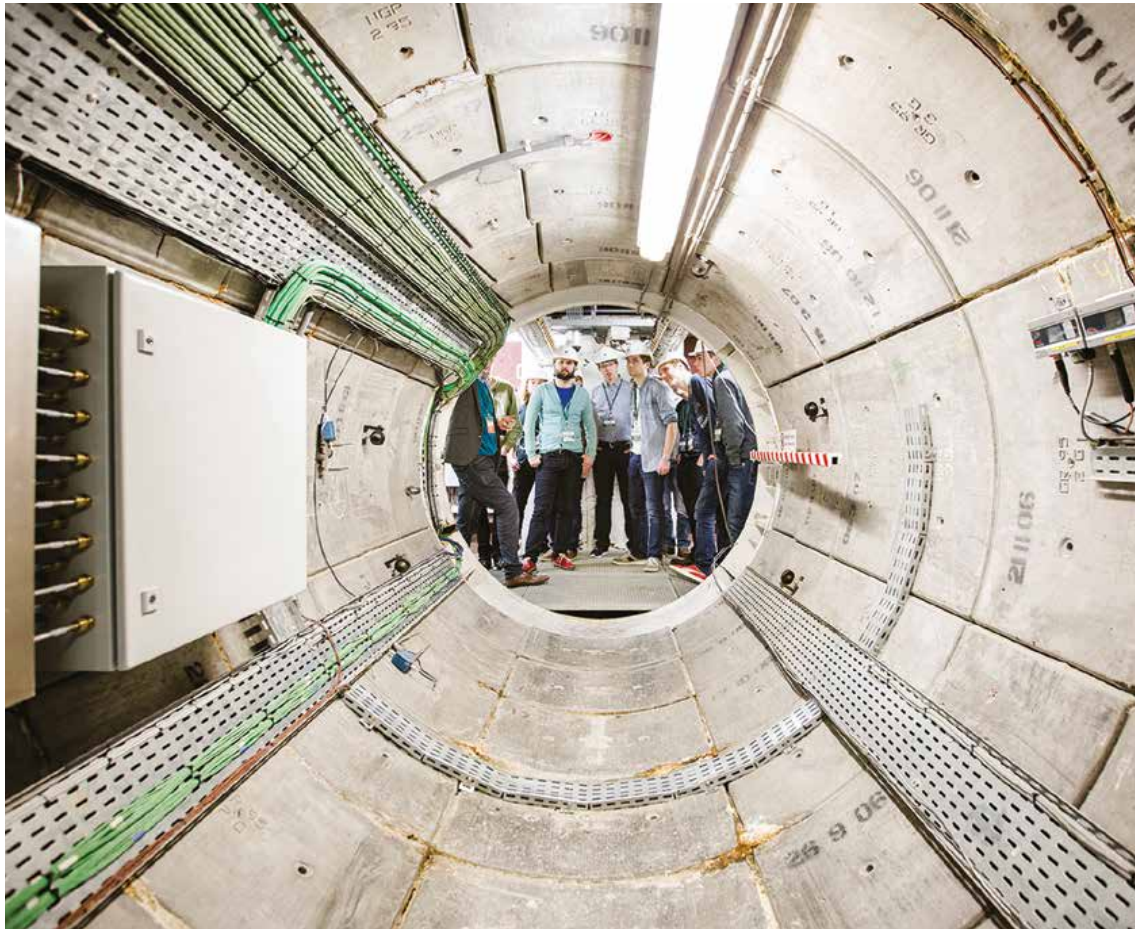
A **building permit** for the shaft 1 renovation project was granted on 8 August 2019 (as part of the environmental permit). The work on site will start in early 2020.

A new **broadcasting licence** was granted on 17 April 2019 by BIPT for the use of the walkie-talkie communication system. It comprises two repeaters and ten walkie-talkies in a first-category radio network with 1 Watt broadcasting power.

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 concept of geological disposal and are the ideal way to present and explain the research that has been going on for the past 39 years. In addition to arranging visits to the exhibition and the URL, EURIDICE has its own website, events and publications to inform a wide audience about its activities within the context of ONDRAF/NIRAS's research programme on geological disposal.



1. Visits

1.1. General

Anyone over the age of 18 can visit EIG EURIDICE and the underground research laboratory. Fifth- and sixth-year secondary school students can visit the permanent exhibition on geological disposal research. These school visits are usually combined with a tour of one of SCK CEN's facilities or a visit to ISOTOPOLIS, the information centre of ONDRAF/NIRAS and Belgoprocess in Dessel. In 2019 "The Bergemeesters" was launched, 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 needs, advantages and disadvantages of constructing a geological repository in a local community. The winning mayor becomes the so-called "Bergemeester"¹. Our aim with this game is to make the visits more dynamic and interesting for young people. By placing more emphasis on discussion and less on detailed information, we hope to encourage them to take part in the societal debate on this matter.

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



Figure 34 - "The Bergemeesters" – new format for school visits

In 2019 EIG EURIDICE welcomed a total of 2,612 visitors in the course of 152 visits to the HADES URL and/or above-ground exhibition on geological disposal (Figure 35). Of these 152 visits, 23 groups took part in "The Bergemeesters" game format, accounting for 637 visitors out of 2,612. Although the number of secondary students remained more or less the same, the total number of visits and visitors is lower than in 2018. This is due to the fact that the renovation work on shaft 1 was originally scheduled to start during the summer of 2019 and would have lasted several months. Many visits were therefore postponed or did not take place. As renovation will finally start in early 2020, underground visits will be stopped during 2020.

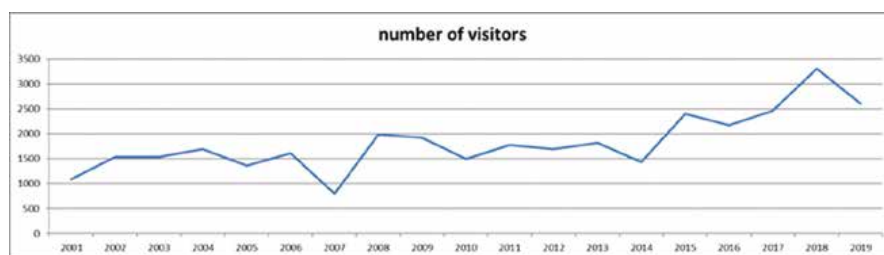


Figure 35 - Number of people visiting EIG EURIDICE since 2001

Figure 36 gives an overview of the different types of visits. Of the 152 visits in 2019, 39 involved sociocultural organisations. These "standard" visits take about two hours (1 hour exhibition, 1 hour tour of HADES URL) and are led by trained guides, who are also in charge of visits at ISOTOPOLIS. Fifty-two of the 152 visits involved direct stakeholders of EIG EURIDICE or were arranged at the request of SCK CEN or ONDRAF/NIRAS. These are designated as VIP or technical visits and include geological disposal experts, journalists, and key political and economic figures. They are given a personalised guided tour by scientific staff, the Communication Manager and/or the Director of EIG EURIDICE, sometimes accompanied by ONDRAF/NIRAS or SCK CEN management.

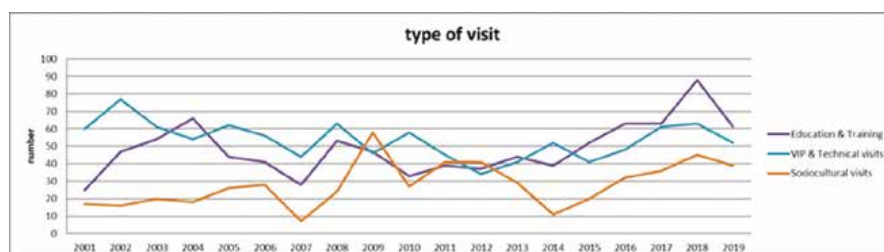


Figure 36 - Trends in the different types of visits

As in the past, the majority of the visits (61) were for training and educational purposes, ranging from secondary school students to university students with a scientific background and adult training courses for people working in the field of nuclear applications.

1.2. VIP visits

On 19 September 2019 the Chairman of China National Nuclear Corporation, Mr Yu Jianfeng, and his high-level delegation visited EURIDICE and its underground research facilities, accompanied by SCK CEN Director-General Eric van Walle. Peter De Preter, Director of EIG EURIDICE, Mieke De Craen, EURIDICE's Team Manager, and Guangjing Chen, scientific collaborator, showed Mr Yu around the HADES URL to apprise him of Belgian research into geological disposal in poorly indurated clay (Figure 37). The aim of the visit was to investigate potential avenues for collaboration in the field of geological disposal research in URLs.

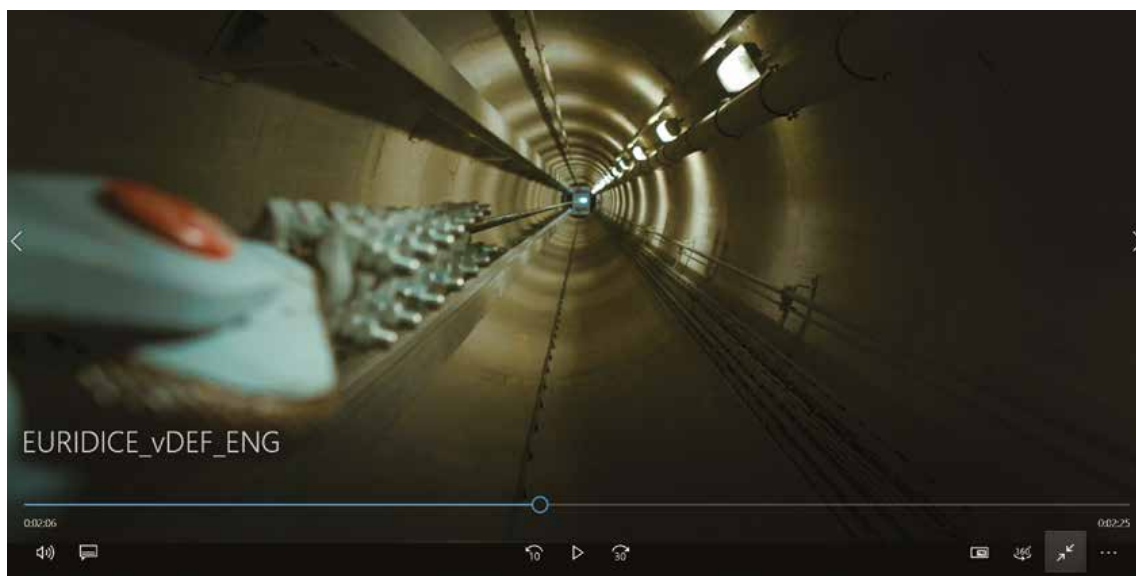


Figure 37 - Visit by Mr Yu Jianfeng, Chairman of China National Nuclear Corporation, and his delegation.

EIG EURIDICE was also delighted to welcome in 2019 the Prince de Ligne together with Major General Albert Husniaux on 22 January, and the Ambassador of Morocco on 6 March. Both visits were organised as part of a visit to SCK CEN and its research facilities.

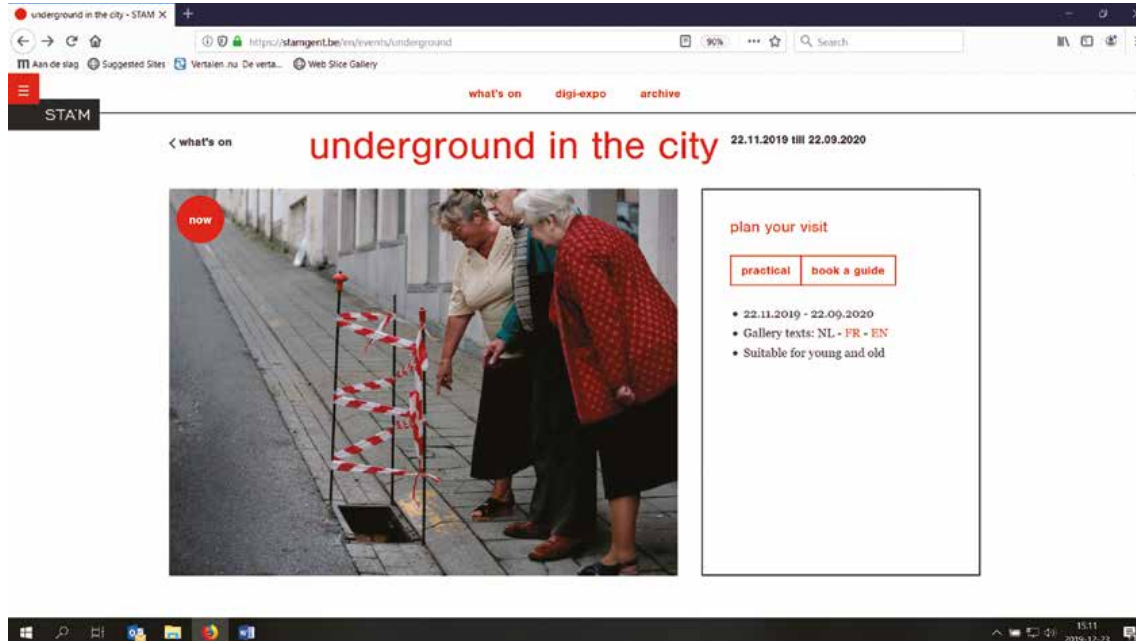
2. New introductory film

During 2019 EURIDICE worked on putting together a new introductory film for visitors. The film was produced and directed by "Het Peloton", an independent production company based in Ghent, and will only be used in the context of visits. The goal of this film is to give visitors a first impression of the nature and origin of radioactive waste and the current conceptual ideas about a geological repository in Belgium. The film is a good starting point for visiting HADES and the permanent exhibition on research into geological disposal.



3. “Underground in the city” exhibition – Ghent City Museum

An exhibition called “Underground in the city” opened at Ghent City Museum on 22 November 2019, focusing on a variety of human activities underground. From foundations and tunnels over pipes, cables and nuclear bunkers to waste storage, all these invisible activities change the underground world and contribute to life on the surface. The exhibition is being staged in association with Studio ORKA and Rotor, a cooperative design practice that investigates the organisation of the material environment.



EIG EURIDICE is contributing to this exhibition by providing information about research on geological disposal of radioactive waste in poorly indurated clays, as well as an actual piece of Boom Clay (Figure 38). The exhibition will run until 22 September 2020.



Figure 38 - Piece of Boom Clay at the “Underground in the city” exhibition – Ghent City Museum

4. Media coverage

On 30 January 2019 VRT NWS launched on its website an item on nuclear energy and management of nuclear waste in the broader context of climate change and energy politics. The item included a film report about the research on geological disposal in HADES and the long-term management strategy for this waste by ONDRAF/NIRAS, and featured Jan Rypens (EIG EURIDICE) and Sigrid Eeckhout (ONDRAF/NIRAS). The same day, the report was used in Terzake to illustrate a discussion between politicians Bert Wollants (N-VA) en Willem-Frederik Schiltz (Open VLD) on the issue.



Figure 39 - VRT NWS: film report on research into geological disposal of radioactive waste with participation from EIG EURIDICE

5. 22nd Exchange Meeting

On 1 October EURIDICE organised the 22nd Exchange Meeting on monitoring of radioactive waste disposal systems at the Lakehouse in Mol. During this meeting, current ideas about monitoring strategies, as well as feedback from the HADES URL, were presented by different speakers from ONDRAF/NIRAS, SCK CEN and Antwerp University. The presentations did not just focus on the scientific aspects, but also took into account the legal requirements and local stakeholders' expectations.



Figure 40 - 22nd Exchange Meeting on monitoring of radioactive waste disposal systems

6. Participation in external events, conferences and meetings

Team members of EIG EURIDICE took part in national and international meetings and events on several occasions in 2019.

On 28 February Arnaud Dizier gave a presentation entitled “Thermo-hydro-mechanical analysis of a geological repository, from the laboratory to the numerical modelling” during an event organised by the SBGIMR (Société Belge de Géologie de l'ingénieur et de Mécanique des Roches) on geological nuclear waste disposal. The presentation summarised the main observations made within the large-scale PRACLAY Heater test and gave an introduction to the thermo-hydro-mechanical modelling of a geological disposal facility.

In March 2019 the IAEA invited EIG EURIDICE to take part in a workshop on “Planning URF experiments” in China. This workshop was organised by IAEA with the aim of helping China to define a hydro-mechanical characterisation programme of the host rock (crystalline rock). Guangjing Chen, as a representative of EURIDICE, gave three presentations about (i) Construction history of the HADES URL, (ii) Characterisation of the Boom Clay hydro-mechanical behaviour and (iii) Numerical simulations supporting the RD&D programme of a URL.

During the “2nd International Conference on Monitoring in Geological Disposal of Radioactive Waste” (Paris, 9-11 April 2019), Jan Verstricht gave a keynote presentation on the results of the demonstrator experimental programme from the Modern2020 project.

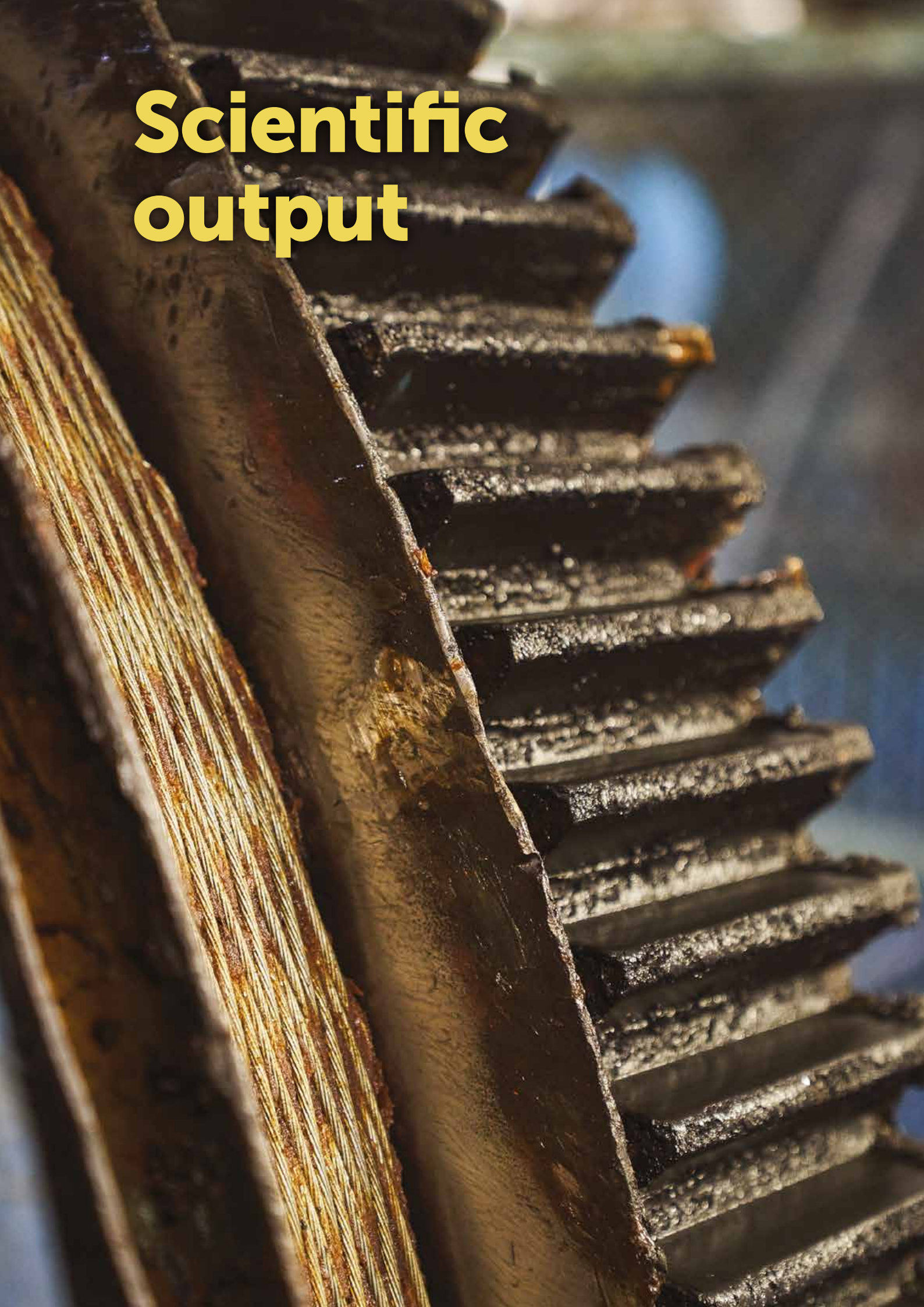
In the context of the Modern2020 project, Jan Verstricht also gave a talk and led a workshop on the instrumentation aspects of demonstrator set-ups during the “Training School about Monitoring in Geological Disposal of Radioactive Waste”, at the Äspö URL (19-26 May 2019).

At the invitation of the IAEA, Xiang Ling Li took part in the Technical Meetings on the Compendium of Results of RD&D Activities carried out at Underground Research Facilities for Geological Disposal, which were organised in February and November 2019 in Vienna. The goal of these meetings is to draw up an inventory of all knowledge and expertise that has been acquired in the different underground research facilities to be able to better integrate and share knowledge on an international level.

As part of the Federal Public Service (FPS) Economy's funding scheme for improvement of radiation and nuclear safety in Eastern Europe, Guangjing Chen delivered a training course on finite element THM code Code_Bright in November 2019 at the Technical University of Slovakia. During the training, he gave a presentation on “Fundamentals: concepts, basic laws and THgM balance equations”. The participants came from various institutions involved in the geological disposal of radioactive waste in Slovakia and the Czech Republic.

To assess the benefits of participation by EURIDICE/SCK CEN in the next phase of the DECOVALEX project, Xiang Ling Li attended the seventh workshop and steering committee meeting of DECOVALEX-2019. The DECOVALEX project is an international research and model comparison collaboration, initiated in 1992, for advancing understanding and modelling of coupled thermo-hydro-mechanical-chemical (THMC) processes in geological systems. DECOVALEX-2019 was the seventh project phase and ran from 2016 until the end of 2019. The next phase should start in the spring of 2020.

Scientific output



REPORTS AND 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* (available on-line 2019), 13 p. [Paper]

Chen G. *Thermal modelling of the PRACLAY heater test*. EUR 18-048. ESV EURIDICE GIE, Mol, Belgium, 2019. 49p. [Report]

Chen G. – *In situ hydraulic conductivity measurement for the Boom Clay around CG and PG* – EUR 18-014. ESV EURIDICE GIE, Mol, Belgium, 2019. 55p. [Report]

De Craen M., Moors H., Verstricht J. *Description of the HADES piezometers used for the study of in situ Boom Clay pore water chemistry*. SCK CEN ER-0329. SCK CEN, Mol, Belgium, 2019. 194 p. [Report]

Schröder T.J., Rosca-Bocancea E., García-Siñeriz J.L., Hermand G., Abós Gracia H.L., Mayor Zurdo J.C., Verstricht J., Dick P., Eto J., Sipilä M., Saari J.M. *Wireless data transmission systems for repository monitoring*. Modern2020 Deliverable D3.2. EC - European Commission, 2019. [Report]

POSTERS AND PRESENTATIONS

Awarkeh M. *Investigation of the long-term behavior of the Boom Clay*. 2019. PhD-day SCK CEN Mol, Belgium. [Poster]

Chen G. *Characterisation of the Boom Clay THMC behaviour*. 2019. Workshop on the RD&D program for the Beishan URF, Beijing, China. [Presentation]

Chen G. *Numerical simulations supporting the RD&D programme of a URF*. 2019. Workshop on the RD&D program for the Beishan URF, Beijing, China. [Presentation]

Chen G., Van Marcke P. *The construction history of the HADES URF*. 2019. Workshop on the RD&D program for the Beishan URF, Beijing, China. [Presentation]

Chen G. *Fundamentals: Concepts, basic laws and THgM balance equations*. 2019. Training of finite element code Code_Bright in Technical University of Slovakia, Bratislava, Slovakia. [Presentation]

Dizier A., Li X.L. *Thermo-hydro-mechanical analysis of a geological repository, from the laboratory to the numerical modelling*. 2019. Journée d'étude du Société Belge de Géologie de l'Ingénieur et de Mécanique des Roches (SBGIMR) sur le stockage géologique des déchets nucléaires, Liège, Belgium. [Presentation]

Matray J.M., Bohnert E., Raunio K., Delépine-Lesoille S., Landolt M., Bertrand J., Kronberg M., Johannesson L., Verstricht J., Mégret P., Martinot E., Rey M., Garcia-Siñeriz J.L. *Methodology for Qualifying the Monitoring Components*. 2019. 2nd Modern2020 International conference on Monitoring in Geological Disposal of Radioactive Waste, Paris, France. [Presentation]

Verstricht J. *Demonstration of monitoring implementation at repository-like conditions (WP4): Approach and Key Messages*. 2019. 2nd Modern2020 international conference on Monitoring in Geological Disposal of Radioactive Waste, Paris, France. [Presentation]

Verstricht J. *40 years of monitoring experience in the HADES URL: performance assessment of installed sensors*. 2019. 22nd Exchange Meeting, Mol, Belgium. [Presentation]

PROCEEDINGS

Matray J.M., Bohnert E., Raunio K., Delépine-Lesoille S., Landolt M., Bertrand J., Kronberg M., Johannesson L., Verstricht J., Mégret P., Martinot E., Rey M., Garcia-Siñeriz J.L. *Methodology for Qualifying the Monitoring Components*. 2019. Modern2020 Final Conference Proceedings: Second International Conference on Monitoring in geological disposal of radioactive waste: Strategies, technologies, decision-making and public involvement. EC - European Commission, 2019. pp. 165-176. [Proceedings]

List of accronyms

AHA	Auscultation Haute Activité
ANDRA	Agence Nationale pour la Gestion des Déchets Radioactifs (FR)
BRIUG	Beijing Research Institute of Uranium Technology
CLIPLEX	CLay Instrumentation Programme for the EXtension of an underground research laboratory
EBS	Engineered barrier system
EC	European Commission
EDZ	Excavation-damaged zone
ESDRED	Engineering Studies and Demonstration of Repository Designs
FANC	Federal Agency for Nuclear Control (BE)
FE	Full-scale emplacement
GSIS	GeoScientific Information System
HADES	High-Activity Disposal Experimental Site
IRSN	Institut de Radioprotection et de Sécurité (FR)
ISOTOPOLIS	ONDRAF/NIRAS's information centre about radioactive waste management, located in Dessel
LTRBM	Long-Term Rock and Buffer Monitoring
Modern2020	Development and Demonstration of monitoring strategies and technologies for geological disposal (within the framework of the Horizon 2020 Euratom Work Programme)
MONA	Mols Overleg Nucleair Afval (local citizen platform on nuclear waste issues in Mol)
NAGRA	Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (CH)
NBS	Natural barrier system
ONDRAF/NIRAS	Belgian Agency for Radioactive Waste and Enriched Fissile Materials (BE)
SCK CEN	Belgian Nuclear Research Centre (BE)
STORA	Studie en Overleggroep Radioactief Afval in Dessel (local citizen platform on nuclear waste issues in Dessel)
TEM	Testing and Evaluation of Monitoring systems
THM	Thermo-hydro-mechanical
THMC	Thermo-hydro-mechanical-chemical
UPC	Universitat Politècnica de Catalunya (ES)
URL	Underground research laboratory
URF	Underground research facility





ESV EURIDICE EIG

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

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