# 2021 and 22


# Activity Report

ESV EURIDICE EIG

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**Activity Report 2021 & 2022**

Ref. EURIDICE/54165858

Approved by:
Hildegarde Vandenhove, Management Board
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 (EIG) between ONDRAF/NIRAS and SCK CEN. It manages and operates the HADES underground research laboratory (URL), carries out research and development activities for the geological disposal of radioactive waste in deep clay formations and communicates on its activities. The EIG EURIDICE was founded in 1995 and the collaboration between SCK CEN and ONDRAF/NIRAS through the EIG is currently established until 2045.

With the start of the public-public partnership (PuP) between SCK CEN and ONDRAF/NIRAS from 1 January 2021, an important change took place in the operating framework of the EIG EURIDICE. Although the PuP does not change the statutory tasks of the EIG, which were established by a notarial deed in April 2019, it creates a new framework of cooperation between the two members of the EIG. This cooperation is structured in domains. EURIDICE contributes to these domains through its research activities, the operational management of the HADES URL and its communication activities.

This Activity Report provides an overview of EURIDICE's main developments and achievements in 2021 and 2022. This period was marked by the events around the 40th anniversary of the HADES URL. Together with its members, ONDRAF/NIRAS and SCK CEN, EURIDICE wanted to seize this opportunity to put the spotlight on the achievements of 40 years of research and development into the geological disposal of high-level and long-lived waste in Belgium. First, a social media campaign was launched featuring videos and podcasts with answers to frequently asked questions about geological disposal. This was followed in April 2022 by the event "40 years of HADES" in the presence of the Minister for Energy, Tinne Van der Straeten, and the Minister of Economy and Employment, Pierre-Yves Dermagne, an event which triggered widespread media attention. The anniversary activities were completed by a scientific event in December 2022 presenting key contributions of the HADES URL to Belgian and international research into geological disposal.

Another milestone was the refurbishment of the oldest access shaft to the HADES URL. The refurbishment was completed in October 2021 when, after an extensive testing period, the new hoisting system became operational. Despite a limited delay due to Covid-19 and some technical and organisational issues, the project was completed within the allocated budget. And, just as important, despite the difficult working environment a 225 m deep shaft poses, the project was executed without any safety incident. With this major renovation, the accessibility of the HADES URL is ensured for the coming decades. This was celebrated by a festive opening by the director of EIG EURIDICE and the Directors-general of ONDRAF/NIRAS and SCK CEN. The occasion was also marked with a short film emphasising the importance of the HADES URL and the success of the EIG project.

In the course of 2021 and 2022, the municipality of Mol granted a new licence to employ personnel in the URL for a period of 20 years (2021-2040), and the nuclear regulator AFCN/FANC extended the operating licence for a class II nuclear facility. This nuclear license was granted for 15 years until 2036. Finally, the environmental permit was renewed and extended until October 2033.

For many years, the PRACLAY Heater test has been at the heart of EURIDICE's research work. The purpose of this test is to verify, on a scale representative of an actual high-level waste disposal facility, that the heat emitted by this type of waste does not adversely affect the containment properties of the clay. After many years of preparation, the heating phase was started in 2014 and the target temperature of 80°C (at the contact between the concrete gallery lining and the clay) was reached in 2015. In 2021 and 2022 we successfully continued this large-scale test and completed 7 years of heating at 80°C. All components of this large-scale test are still operating as expected and the interim results and findings confirm that the favourable properties of the Boom Clay for geological disposal are not negatively affected by the heating. The results and findings of the PRACLAY Heater test resulted in several publications in reputable scientific journals in 2021 and 2022. Such publications form an important pillar of the scientific basis for geological disposal and of the knowledge management of the EIG EURIDICE. In this way, the results of the PRACLAY Heater test are peer reviewed and are part of the wider scientific domain contributing to the preservation of this knowledge and expertise. The heating phase of the Heater test will continue until 2025 when, after 10 years of heating at 80°C, a cooling and dismantling phase is planned.

Due to the refurbishment of shaft 1 and the COVID-19 pandemic, EURIDICE only received a small number of visitors in 2021 and 2022: a total of around 400 in 2021 and around 1000 in 2022. A lot of time and effort was spent to develop a roadbook for future visits to Tabloo and the HADES URL. Tabloo is a new communication centre which opened in 2022 in Dessel and which provides information about radioactivity, radioactive waste and disposal for a general public. Visits to the HADES URL focused more on technical-scientific actors and those who play an important role in the decision-making process for geological disposal.

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 URL 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 (sometimes also referred to as deep 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 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.

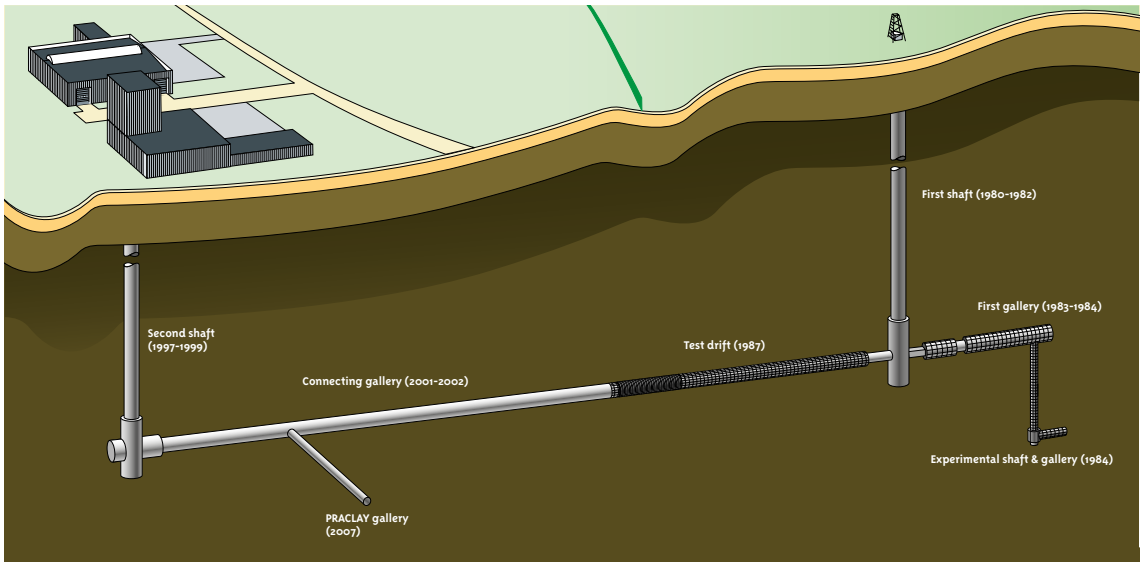



Figure 1 – The underground research laboratory HADES (High-Activity Disposal Experimental Site)

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

After 40 years of research in and around the HADES URL, a great deal of expertise and know-how has been acquired in different scientific and technological fields, of key importance for developing an underground radioactive waste disposal facility in poorly indurated clay formations such as the Boom Clay. The scientific and technological expertise of EIG EURIDICE focuses on three areas:

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

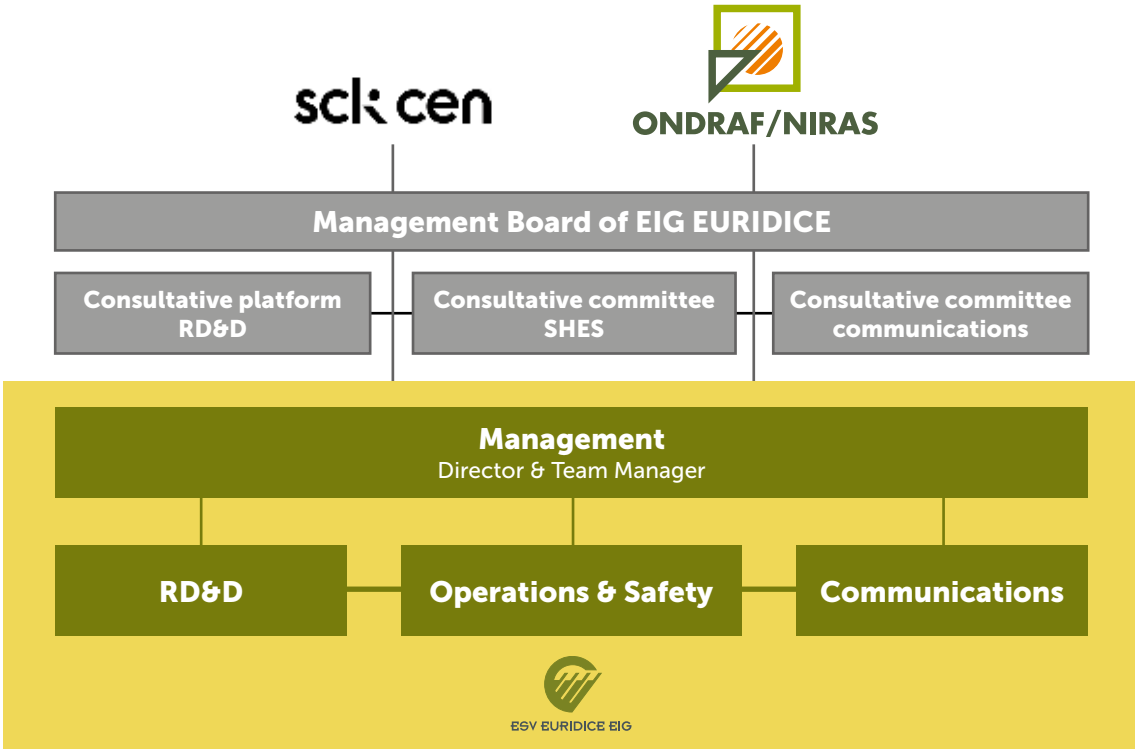
EIG EURIDICE's first area of expertise has evolved significantly over the years, with excavation and construction of the HADES URL evolving from semi-manual and slow to industrial, using tailor-made tunnelling machines. The tunnelling techniques used to excavate in poorly indurated deep clay layers,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

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

With its RD&D activities and fields of expertise, ESV EURIDICE contributes to the national program for the disposal of high-level and long-lived waste managed by ONDRAF/NIRAS. In 2022, the Federal Government took a first national policy decision for the long-term management of high-level and long-lived waste in Belgium. This first decision, in the form of the Royal Decree of 28 October 2022, establishes geological disposal as a reference solution. A second national policy decision will define the decision-making process for the implementation of geological disposal. ONDRAF/NIRAS will make a proposal for this decisional process, based on a national debate that will be organised in 2023 and 2024.

# EIG EURIDICE today

# 1. Organisation




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

The board members in the period 2021-2022 were as follows:

- Marc Demarche, Chairman, Director-General of ONDRAF/NIRAS
- Philippe Lalieux, Director long-term management ONDRAF/NIRAS
- Eric van Walle, Director-General of SCK CEN (until 20 June 2022)
- Peter Baeten, Director-General of SCK CEN (from 21 June 2022)
- Hildegarde Vandenhove, Director of the Environment, Health and Safety Institute of SCK CEN

Figure 2 – Meeting of the Management Board

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

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

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

To achieve its strategic and operational objectives in a quality manner, the management system of EIG EURIDICE has been certified since 2007 according to ISO 9001. The current certificate is valid until 23 September 2024 and is audited by DNV Belgium, an assurance and risk management company. In addition to efficiency and effectiveness, EURIDICE attaches great importance to the continuous improvement of its processes through internal audits, education and training of its staff and awareness of risks.

## 2. EIG EURIDICE team

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

**Director:**
Peter De Preter

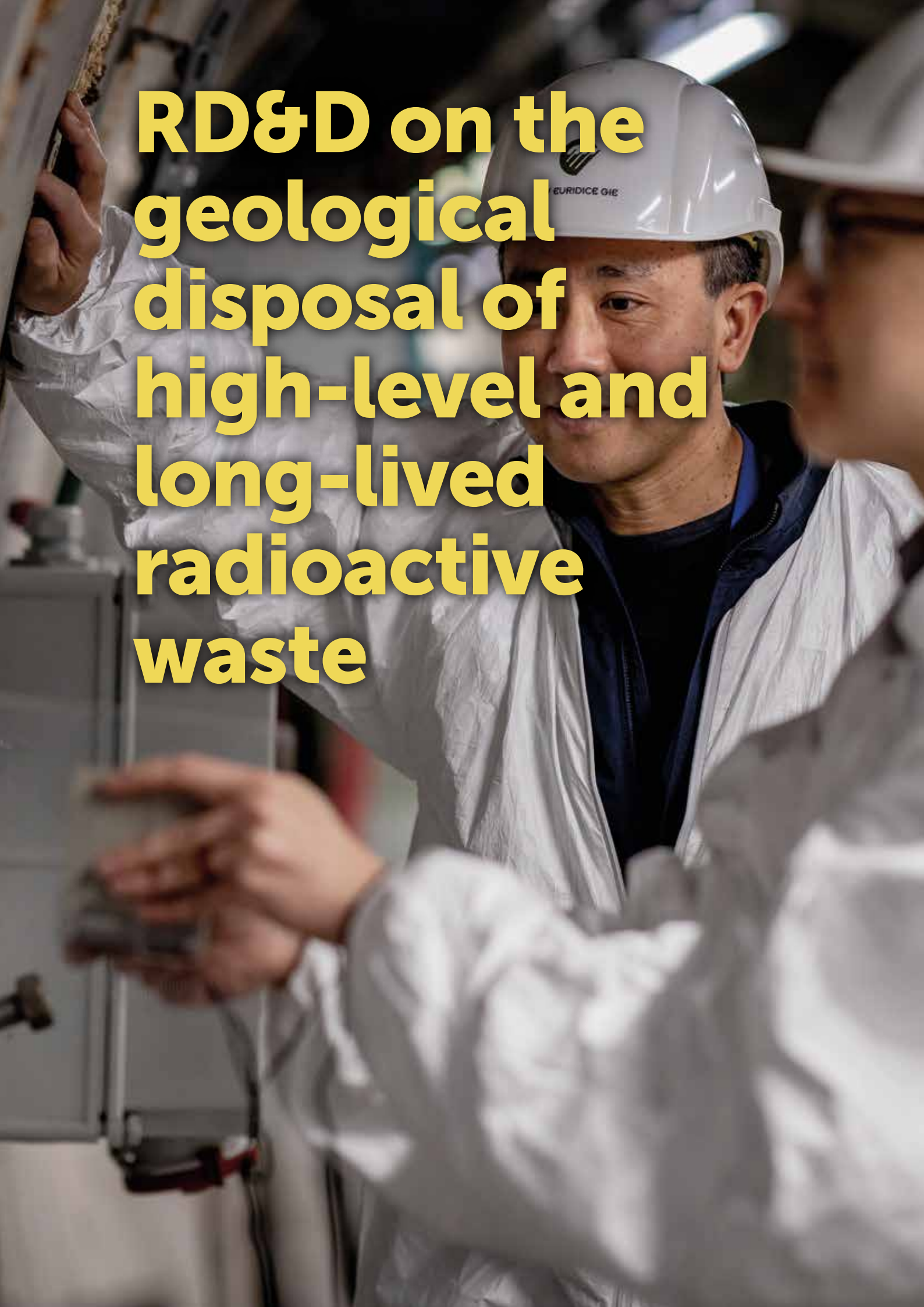
**Team Manager:**
Mieke De Craen

**Management Assistant & QA:**
Caroline Poortmans

**RD&D process:**
Xiang Ling Li – scientific coordinator
Arnaud Dizier – scientific collaborator
Guangjing Chen – scientific collaborator
Dries Nackaerts – scientific collaborator
Jan Verstricht – scientific collaborator
Temenuga Georgieva – scientific collaborator

**Operations and safety process:**
Kevin Schuurmans – manager
Luc Mariën - project engineer (until 31 May 2022)
Dries Nackaerts – technical collaborator
Christiaan Lefèvre – technical collaborator (until 30 October 2021)
Bram Olijslagers – technical collaborator
Johan Peters – technical collaborator
Bert Vreys – technical collaborator

**Communication process:**
Jan Rypens – coordinator (until 30 September 2022)
Mieke De Craen – coordinator (from 1 October 2022)
Els van Musscher – administrative collaborator




# RD&D on the geological disposal of high-level and long-lived radioactive waste

On the occasion of the 40th anniversary of HADES, EURIDICE compiled the main achievements of 4 decades of RD&D in the HADES URL in a Special Publication of the Geological Society London: "*Geological Disposal of Radioactive Waste in Deep Clay Formations: 40 Years of RD&D in the Belgian URL HADES*". Section 1 of this part on RD&D activities provides more explanation about this publication.

Furthermore, in 2021 and 2022, EIG EURIDICE's scientific activities continued to contribute to the RD&D programme to assess the safety and feasibility of geological disposal of high-level and/or long-lived radioactive waste in a deep clay formation in Belgium. This includes the follow-up of the large-scale PRACLAY Heater test that has been running since 2014. Section 2 provides an overview of the main observations obtained from the PRACLAY Heater test.

After 8 years of heating, the experimental set-up is still functioning as intended and the test components are evolving as expected. Over this period, the THM behaviour of the clay has been monitored and analysed. This allowed us to improve our interpretation of the PRACLAY Heater test and our understanding of the THM behaviour of the clay. Results confirmed what we knew from lab tests and previous in-situ experiments and enabled refining this knowledge. No negative impact on the clay as a potential natural barrier for geological disposal has been observed.

Section 3 describes EURIDICE's work to support ONDRAF/NIRAS in its RD&D programme on the technical feasibility of a geological disposal facility. This includes an evaluation of the stability of the Connecting gallery in the HADES URL. An analysis of the stresses inside the concrete lining showed that these remain below the allowable stress and are far from the ultimate stress of the concrete lining. The gallery lining is also frequently inspected and all cracks observed on the surface of the concrete segments are mapped. Other work included a state of the art of the in-situ stress in the clay at the level of the HADES URL and a study of the transferability of the geomechanical parameters of Boom Clay around the HADES URL to other locations and depths.

Since construction work on the HADES URL began in the early 1980s, many experimental set-ups of different sizes and for various purposes have been implemented in the HADES URL. A closer investigation of the instrumentation can therefore give us valuable insight into long-term sensor performance and which factors determine a successful monitoring operation in the long term. This knowledge will be very relevant for the monitoring design of future large-scale experimental set-ups and optionally for a radioactive waste repository. The first study, from 2015 until 2018, dealt with the performance assessment of the instrumentation installed as part of the CLIPEX project. In 2021 and 2022 this work continued focusing on the instrumentation used for the PRACLAY Heater test. This is discussed in section 4.

Section 5 gives an overview of EURIDICE's international activities, including work for the IAEA and several Work Packages of the European Joint Programme on Radioactive Waste Management and Disposal (EURAD). Finally, section 6 gives an update of the four PhDs that EURIDICE supports.

# 1. Special Publication "*Geological Disposal of Radioactive Waste in Deep Clay Formations: 40 Years of RD&D in the Belgian URL HADES*"

To highlight the achievements of 40 years of RD&D in the HADES URL, EURIDICE organised a Special Publication of the Geological Society London titled "Geological Disposal of Radioactive Waste in Deep Clay Formations: 40 Years of RD&D in the Belgian URL HADES". Guest editors of this publication are Xiang Ling Li and Mieke De Craen (EURIDICE), Maarten Van Geet (ONDRAS/NIRAS) and Christophe Bruggeman (SCK CEN).

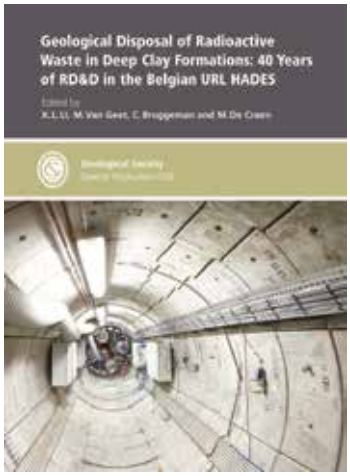



Figure 3 – The Special Publication "*Geological Disposal of Radioactive Waste in Deep Clay Formations: 40 Years of RD&D in the Belgian URL HADES*"

This publication presents several key contributions of the HADES URL to both national and international research into geological disposal. More specifically, the publication contains the following papers:

1. Li, X.L., Van Geet, M., Bruggeman, C. and De Craen, M. Geological disposal of radioactive waste in deep clay formations – Celebrating 40 years of RD&D in the Belgian URL HADES.
2. Li, X.L., Neerdael, B., Raymaekers, D. and Sillen, X. The construction of the HADES Underground Research Laboratory and its role in the development of the Belgian concept for a deep geological repository.
3. Li, X.L., Dizier, A., Chen, G., Verstricht, J. and Levasseur, S. 40 years of investigation into the thermo-hydromechanical (THM) behaviour of Boom Clay in the HADES URL.
4. Chen, G., Li, X.L., Dizier, A., Verstricht, J., Sillen, X. and Levasseur, S. Characterisation of Boom Clay anisotropic THM behaviour based on two heating tests at different scales in the HADES URL
5. Dizier, A., Scibetta, M., Armand, G., Zghondi, J., Georgieva, T., Chen, G., Verstricht, J., Li, X.L., Léonard, D. and Levasseur, S. Stability analysis and long term behaviour of deep tunnels in clay formation
6. Verstricht, J., Nackaerts, D., Li, X.L., Léonard, D., Levasseur, S. and Van Geet, M. Assessment of long term sensor performance based on a large THM experiment in the HADES URL.
7. Aertsens, M., Weetjens, E., Govaerts, J., Maes, N. and Brassinnes, S. CP1 and Tribicarb-3D: unique long-term and large-scale in-situ migration tests in Boom Clay at the HADES Underground Research Laboratory.
8. Govaerts, J., Maes, N., Durce, D., Aertsens, M., Brassinnes, S. Coupled flow and transport modelling of a large-scale in-situ migration experiment with $^{14}C$-labelled natural organic matter colloids in Boom Clay.
9. Jacops, E., Yu, L., Chen, G. and Levasseur, S. Gas transport in Boom Clay: Role of HADES URL in process understanding.
10. De Craen, M., Moors, H., Honty, M. and Van Geet, M. The role of the HADES URL in the better understanding of the Boom Clay pore water geochemistry.
11. Kursten, B., Caes, S., de Souza, V. and Gaggiano, R. Lessons learned from the in-situ corrosion experiments in the HADES URL.
12. Armand, G., Plas, F., Talandier, J., Dizier, A., Li, X.L. and Levasseur, S. Contribution of HADES URL to the development of the Cigéo project, French industrial centre for geological disposal of high-level and long-lived intermediate-level radioactive waste in a deep clay formation.
13. Nussbaum, C., Bernier, F., Bleyen, N., Bossart, P., Bruggeman, C. De Cannière, P., Fierz, T., Jaeggi, D., Neerdael, B., Valcke, E. and Volckaert G. 25 years of cross-fertilization between HADES and Mont Terri rock laboratory.

14. Bernier, F., Detilleux, V., Lemy, F., Pochet, G.J., Surkova, M., Volckaert, G. and Mommaert, C. Underground Research Laboratories, an Important Support to the Belgian Regulatory Body's Research and Development Programme and the Management of Uncertainties
15. Ben-Hadj-Hassine, S., Davies, C. and Garbil, R. 45 years of joint research programmes on geological disposal of radioactive waste and the pioneering role of the HADES Underground Research Laboratory.
16. Mayer, S.J., Van Marcke, P., Jung, H., Thompson, P. and Acharya, G. Important roles of underground research laboratories for the geological disposal of radioactive wastes: An international perspective
17. Geysmans, R., Silvikko De Villafranca, M. and Meskens, G. Making the future in the present: Using Science and Technology Studies to reflect on 40 years of research in the HADES Underground Research Laboratory.

Although most of the abstracts were online by the end of 2022[1], the publication of the book is expected in early 2023.

In addition to highlighting these achievements, the publication also contributes to the preservation of scientific knowledge. Publishing the scientific and technical results of the work in peer-reviewed journals is an important pillar of the EIG EURIDICE knowledge management approach.

## 2. The PRACLAY Heater test

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

The PRACLAY project consists of several sub-projects and experiments. The aims of these experiments are:
1. To demonstrate the feasibility of underground construction in the Boom Clay.
2. To demonstrate the feasibility of the disposal concept for high-level waste in the Boom Clay.
3. To confirm and expand knowledge about the thermo-hydro-mechanical-chemical behaviour of the Boom Clay and the gallery lining.

The different parts of the PRACLAY Seal & Heater experimental set-up are shown in Figure 4. 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. The PRACLAY Seal and Heater tests are extensively instrumented to control the heating process and for the purpose of the experimental follow-up.

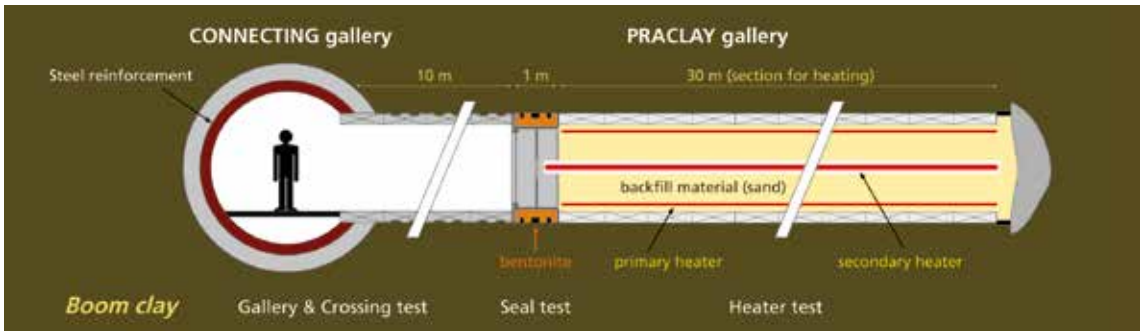



Figure 4 – Design of the PRACLAY experiment

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.

[1] https://www.lyellcollection.org/toc/sp/536/1

For the purpose of the Heater test, part of the PRACLAY gallery (30 m) has been closed off with a seal structure and will be heated for a period of 10 years at a temperature of 80°C at the interface between the gallery lining and the clay. The Heater test has been designed in such a way that it is representative of the conditions that would be expected in a high-level waste repository for both vitrified high-level waste and spent fuel. After the construction of the PRACLAY gallery in 2007 and the design and installation of the seal (2007-2010), installation of the heating system started in 2010 (primary heater) and was completed in 2014 (secondary heater). A detailed report about the design, preparation and installation of the PRACLAY Heater test was published in 2013, upon conclusion of the installation phase of the experiment (EUR 13-129).

On 3 November 2014, the heating system was switched on 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 and the start of the stationary phase. A detailed report on the experimental evolution during the start-up phase was published in 2016 (EUR_PH_16_025).

Since then, the PRACLAY Heater test has been running successfully. The experimental set-up is functioning as intended and the test components are evolving as expected. The power of the heating system has been systematically adjusted to maintain the temperature at this interface constant at 80°C. 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.

In 2018, a first report (EUR_PH_17_043) was published in which the test results were analysed. It summarises the observations from the start-up phase and the first two years of the stationary phase at 80°C. A second report (EUR-20-058 /ER) was published in 2021. It summarises the main observations of the test and presents the numerical interpretation of the test measurements. It also explains how these numerical simulations contribute to the refinement of the thermo-hydro-mechanical parameters of the Boom Clay.

## 2.1. Evaluation of the PRACLAY Heater test

By the end of 2022, the PRACLAY Heater test had been running for more than eight 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. Figure 5 shows how the temperature at the interface between the gallery lining and the clay is maintained at 80°C during the stationary phase of the test.

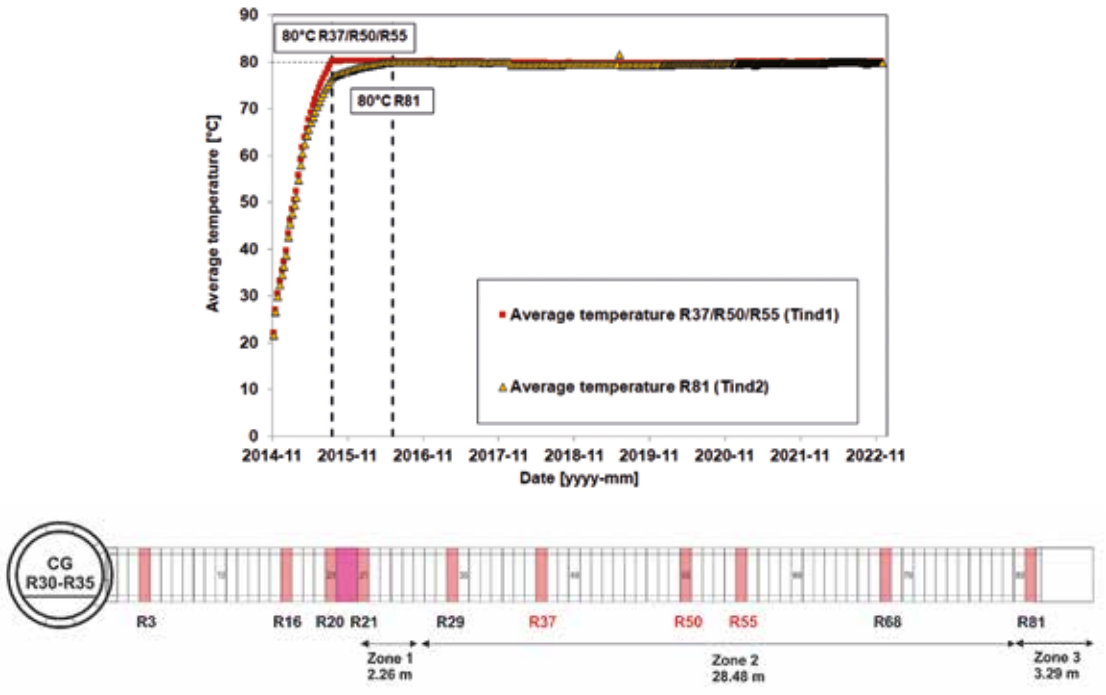



Figure 5 – Average temperature evolution measured using the extrados sensors in gallery rings R37, R50 and R55 (Tint_1) and R81 (Tint_2)

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. This is evident, among other things, from the pore water pressure in the backfilled part of the PRACLAY gallery, shown in Figure 6. As can be seen, the pore water pressure is maintained at a level of approximately 2.8 MPa.

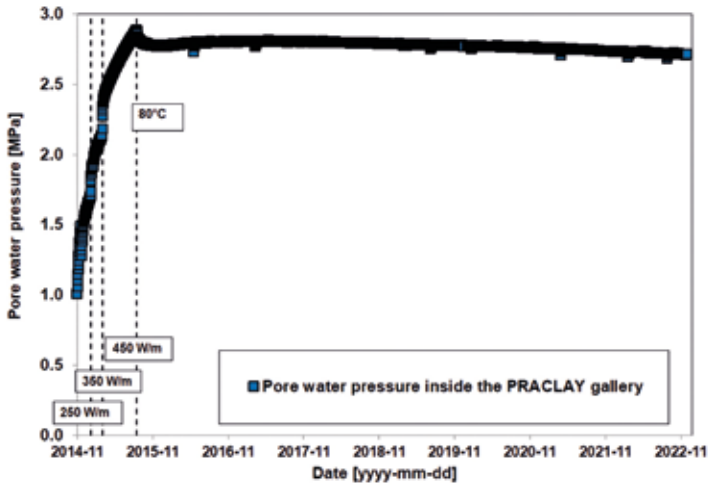



Figure 6 – Pore water pressure evolution in the backfilled part of the PRACLAY gallery

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.

The monitoring programme allows for overall follow-up and control of the experiment, even though a number of sensors have failed (e.g., embedded strain gauges in the concrete lining blocks) or have delivered data with artefacts, thanks to the extensive network of instrumentation and the redundancy of critical sensors. The dedicated effort to analyse the long-term performance of all PRACLAY related sensors is described further (section 4).

The observations from more than eight years of heating have confirmed our knowledge of the THM behaviour of the Boom Clay gained from surface laboratory investigations and smaller-scale in-situ heating experiments. Heating on a large scale has not modified its favourable properties as a natural barrier for a potential high-level waste disposal system in poorly indurated clay.

An internal report entitled "*Scientific interpretation of the first years of the PRACLAY Heater test*" was published in 2021. This report summarises the scientific interpretation of the first 5-6 years of observations from the PRACLAY Heater test by means of numerical THM models.

## 2.2. Refining the characterisation of the Boom Clay

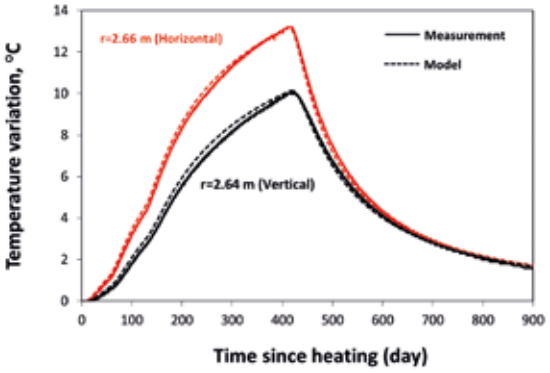
Constant efforts have been made to improve and support the interpretation of the PRACLAY Heater test, enabling us to improve and confirm the characterisation of the Boom Clay. The stepwise improvement in the interpretation of the PRACLAY Heater test is largely based on knowledge gained from the small-scale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

**CHARACTERISATION OF BOOM CLAY ANISOTROPIC THM BEHAVIOUR BASED ON NUMERICAL SIMULATIONS**

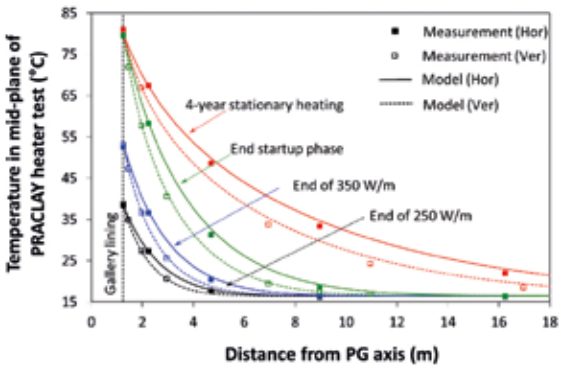
Many numerical modelling studies have been carried out to interpret the observed temperature and pore water pressure evolution around both the ATLAS heater borehole and the PRACLAY gallery. This supported the confirmation and refinement of the cross-anisotropic THM constitutive models and associated parameter values obtained from a laboratory characterisation programme.

The small-scale ATLAS IV Heater test is first analysed by a 3D coupled THM model. An extensive sensitivity analysis was performed to demonstrate that the model is able to reproduce both the magnitude and the trend of the pore water pressure evolution at all filters during the heating and cooling cycle of the test (Figure 7a, Figure 7c and Figure 7e). The analysis confirmed that the proposed mechanical model for the Boom Clay allowed deriving a set of anisotropic THM parameter values for the Boom Clay.

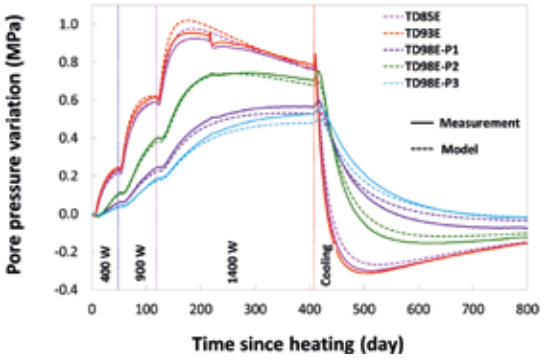
These results are then used to support the numerical interpretation of the measurements in the mid plane of the PRACLAY Heater test. This was done using a 2D-PS coupled THM model. This model uses the measured temperature at lining extrados in the mid plane as the thermal boundary condition and the measured pore water pressure in the PG at the lining intrados as the hydraulic boundary condition. The results from the model match well with the measurements, both within the EDZ and in the far field (Figure 7b, Figure 7d and Figure 7f).



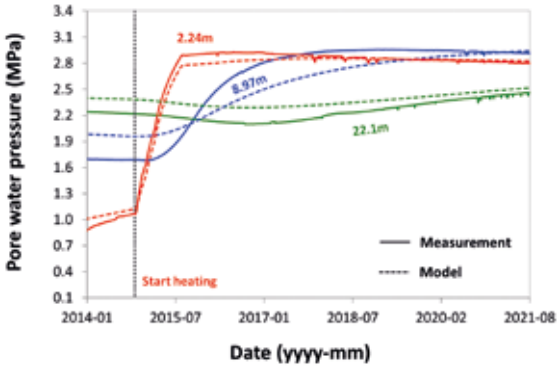

(a) Temperature around ATLAS IV Heater



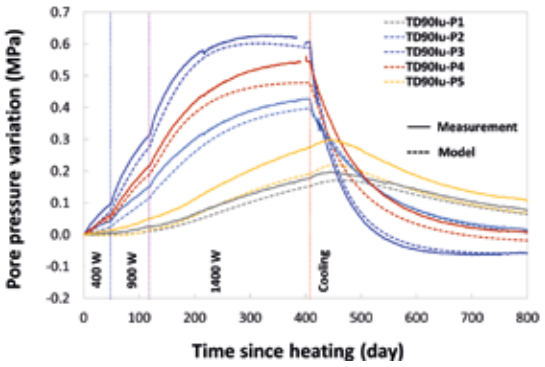

(b) Temperature around PRACLAY Heater



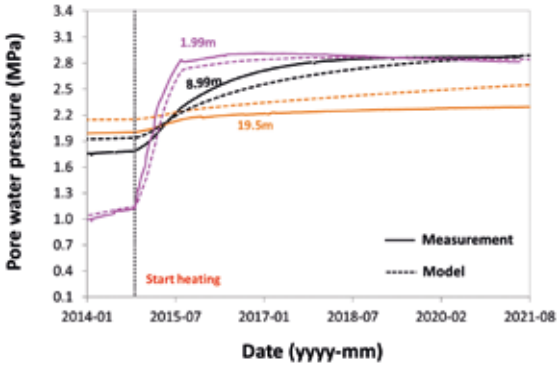

(c) Pore water pressure in the horizontal plane of ATLAS IV Heater




(d) Pore water pressure in the horizontal plane of PRACLAY Heater




(e) Pore water pressure above the ATLAS IV Heater




(f) Pore water pressure above the PRACLAY Heater

Figure 7 – Numerical interpretation of the THM responses around the ATLAS IV Heater and the mid-plane of PRACLAY Heater

This demonstrates that the mechanical model and the anisotropic THM parameter values derived from both the small-scale ATLAS IV and the large-scale PRACLAY Heater tests are capable of reproducing measurements from both in-situ tests. This conclusion strengthens our confidence in the Boom Clay THM characterisation results.

This analysis and the conclusions that were drawn from it regarding the THM properties of Boom Clay are explained in detail in two papers published in 2022:

- *"Determination of the Anisotropic Thermal Conductivity of the Boom Clay based on a Combined Numerical Interpretation of Two in-situ Heater Tests at Different Scales"* in*: "Acta Geotecnica";* and
- *"Characterization of Boom Clay anisotropic THM behaviour from the small scale ATLAS Heater Test in support of the interpretation of the large scale PRACLAY Heater Test in the HADES URL"* in*: "Geological Society, London, Special Publications: Geological Disposal of Radioactive Waste in Deep Clay Formations: 40 Years of RD&D in the Belgian URL HADES."*

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

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

This study aims to identify a range of the Boom Clay thermal conductivity values based on an inverse analysis of the ATLAS IV and PRACLAY Heater tests. The inverse analysis considered the temperature measurements of 29 sensors around the ATLAS Heater test and 31 sensors around the PRACLAY Heater test. A 3D thermal model was developed and a large number of cases were modelled. Each case uses a different combination of thermal conductivity values $(\lambda_h, \lambda_v)$. For each sensor, a pair of optimal values $(\lambda_h^*, \lambda_v^*)$ was then derived for which the difference between the measured and modelled temperatures was minimised.

The methodology applied is described in an internal report: *"Identification of the Boom Clay thermal conductivity range based on an inverse analysis of the ATLAS IV and PRACLAY Heater Tests"* (Ref. EUR-PH-22-072). The analysis resulted in a range of thermal conductivity values: $\lambda_h$=1.55-1.95 W/(mK) and $\lambda_v$=1.10-1.25 W/(mK).

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

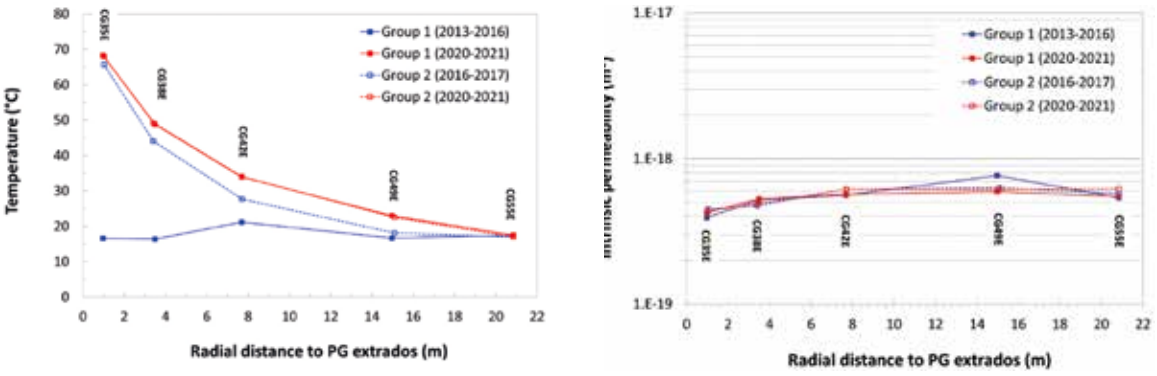
An in-situ permeability test campaign was carried out in 2020-2021 by conducting tests on 112 filters in boreholes around the PRACLAY gallery. This test campaign is a continuation of the previous test campaigns carried out before April 2018.

The aims of the 2020-2021 test campaign are as follows:

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

A detailed analysis and interpretation of the permeability measurement results from the 2020-2021 test campaign were carried out. The outcomes of this analysis have been published in an internal report *"In-situ hydraulic conductivity measurement for the Boom Clay around the Connecting gallery and PRACLAY gallery: Test campaign 2020-2021"* (Ref. EUR-PH-21-068).

The 2020-2021 test campaign is the first systematic and comprehensive campaign to be conducted when the clay temperature around the PRACLAY gallery has increased significantly. The highest temperature around the PRACLAY gallery is 68°C and the zone with elevated temperature extends to 16 m from the PRACLAY gallery. Both the temperature increase and its spatial extent are sufficient to investigate the thermal impact on the Boom Clay permeability. Figure 8 shows that the intrinsic permeability does not change significantly with temperature. The two groups of filters are illustrated in Figure 9.




(a) (b)

Figure 8 – Profiles of (a) temperature and (b) intrinsic permeability measured at the filters of groups 1 and 2

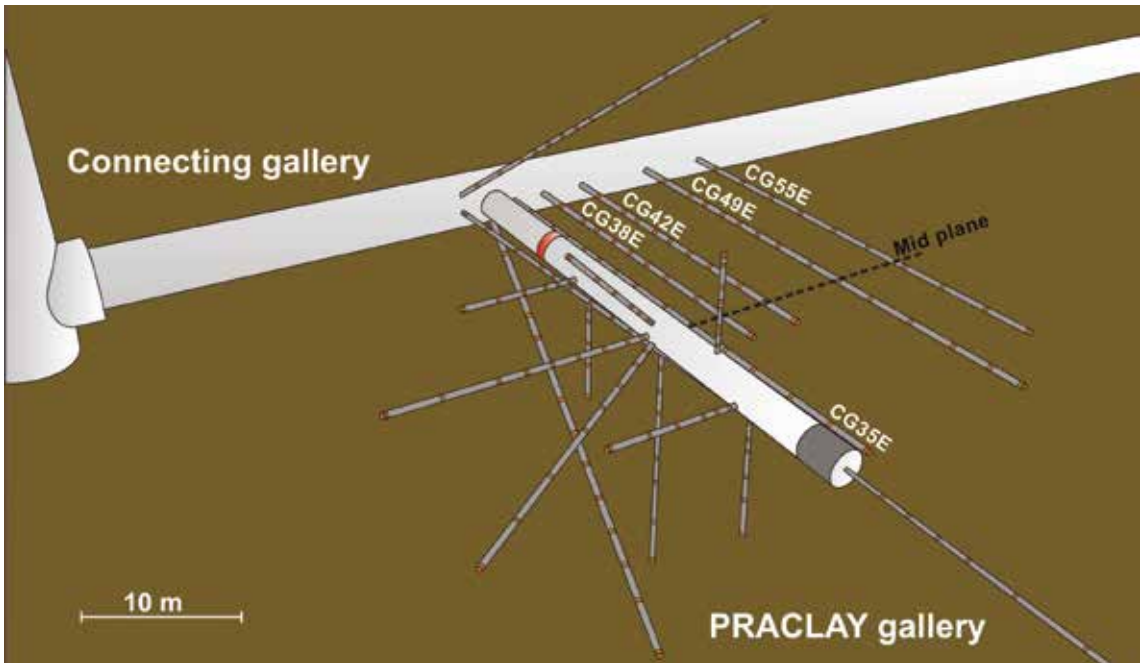



Figure 9 – Two groups of filters selected from CG boreholes CG35E, CG38E, CG42E, CG49E and CG55E

The test campaign also confirmed some observations from previous campaigns. Higher permeabilities could be linked to the lithology of the Boom Clay formation, such as more silty clay in the transition zone, the 'Double Band' and septaria. Higher permeabilities are also observed in the EDZ. However, these decreased over time and remain in the same order of magnitude as the permeabilities of undisturbed clay.

## PRACLAY PORE WATER SAMPLING AND COMPOSITION ANALYSIS

When assessing a rock formation for its suitability as a potential host rock for the disposal of radioactive waste, knowledge about the composition of the pore water is essential. It determines the speciation and solubility of radionuclides and is required as an initial or boundary condition to evaluate the interactions with other repository components.

The HADES URL offers the possibility to extract pore water from Boom Clay and analyse its composition. This resulted in a characterisation of the Boom Clay pore water, including insight into the impact of perturbing processes such as oxidation. These analyses are carried out by SCK CEN's Waste and Disposal Group, with the support of the EIG EURIDICE.

As a result, the pore water composition of the Boom Clay in Mol is relatively well known at the HADES URL depth of 225 m and at the corresponding in-situ temperature of 16°C. However, it is less known how the pore water composition will change near disposal galleries with heat-emitting waste.

The PRACLAY Heater test offers the possibility to examine the impact of an elevated clay temperature on the composition of the pore water. Therefore, two in-situ sampling campaigns were conducted in 2021 and 2022. During these campaigns, 8 piezometer filters placed around the PRACLAY Heater test and exposed to variable temperatures between 36 and 69°C were sampled and analysed for their pore water and gas composition and microbial characteristics.

The pore water and gas compositions were then evaluated as a function of the temperature and compared to scoping calculations using a geochemical computer code. The microbial presence and activity were also evaluated as a result of temperature increase. It was observed that the concentrations of most major cations and anions increased with increasing temperature. This was predicted by the geochemical model that takes into account the solubility of minerals and cation exchange mechanisms.

## 2.3. Preparation of the cooling phase

The stationary phase of the PRACLAY Heater test was planned to last 10 years. This means that the heating phase would end in 2025 after which the cooling phase could start. Only after the PRACLAY gallery has cooled down sufficiently can the experimental setup be dismantled.

In March 2022, a first brainstorm meeting was organised with ONDRAF/NIRAS to:
- check whether the objectives of the heating phase are being met
- discuss the possible cooling strategy, i.e., how to reduce the heating power
- develop a common vision of the scientific goals for this phase

The meeting concluded that the heating phase has so far produced the scientific outcomes that were sought. Regular meetings will be organised between now and 2025 to further monitor these outcomes and define the cooling strategy and action plan to implement that strategy.

When defining the cooling strategy, the main priority is to ensure the integrity of the experimental set-up and the safety of the workers who will carry out the subsequent dismantling of that experimental set-up. Therefore, numerical simulations will be performed to evaluate the impact of the different cooling scenarios on the stability of the gallery lining and seal.

Another important consideration concerns the scientific lessons that can be learnt from the cooling phase. This phase provides an opportunity to enhance our understanding of the clay's THM behaviour gained during the heating phase. The measurements of the cooling phase will complement the measurements of the heating phase for the validation and the refinement of THM models and the associated parameter values of the Boom Clay. The cooling strategy must therefore be well controlled to enable a sound scientific interpretation of the measurements during the cooling phase. At the same time, disturbances caused by the cooling phase, like, for instance, unrealistic underpressures in the Boom Clay, must be kept to a minimum in order not to affect the properties of the materials too much.

# 3. Repository feasibility studies

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

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

## 3.1. 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 10 illustrates typical strain evolution in a concrete segment, in ring 30 (R30) near the PRACLAY gallery, which has displayed continuous and slow evolution without any abrupt changes, except during excavation of the PRACLAY gallery. The effect of the start-up phase of the Heater test was marked by a change in slope and a slight increase in the strain rate; the latter tends to stabilise after a few years of heating.

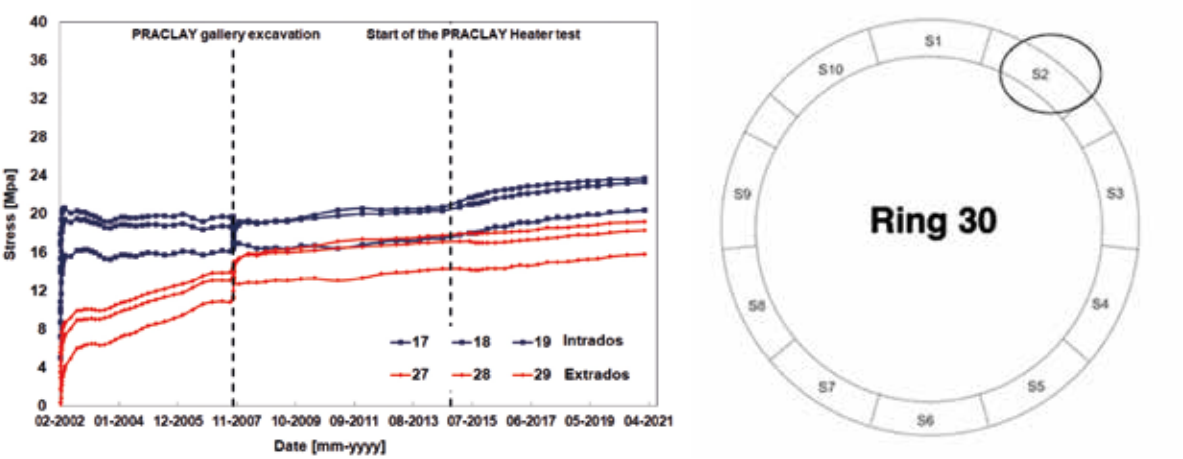


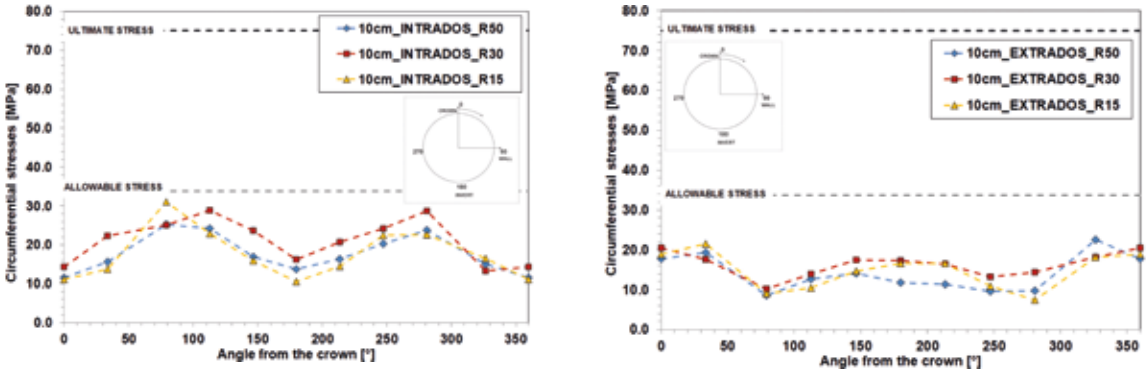

Figure 10 – Typical evolution of the strain in the segmented concrete lining (R30) of the Connecting gallery since the start of the measurements

A mechanical analysis of the Connecting gallery was initiated in 2012 at EURIDICE in collaboration with SCK CEN and ENGIE TRACTEBEL. Initially, the goal was to assess the stress state of three instrumented rings based on the strain gauge measurements. After this initial analysis, the scope of the study was extended to include an evaluation of the pressure acting on the lining and a general discussion on the validity of the approach used for the galley design, which is a critical issue for gallery stability and repository gallery design. This study provided valuable information on the state of the Connecting gallery, though some questions remained unanswered, such as the influence of the radial joints on the overall results and the choice of constitutive law for the concrete and the Boom Clay. Moreover, a proper monitoring strategy still had to be defined.

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

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

The last years have focused on determining the stresses inside the concrete lining using stress measurements along the circumference at the gallery lining (see Figure 11). It is observed that the stresses remained below the allowable stress and are far from the ultimate stress of the concrete lining. It can also be seen that the stress distribution is anisotropic. The compressive stresses at the intrados are higher at the sides (at 90° and at 270°) than at the top and bottom. The opposite is true for the stresses at the extrados. This behaviour is the result of the in-situ anisotropic stresses where the vertical stress (4.5 MPa) is greater than the horizontal one (3.9 MPa).




(a) (b)

Figure 11 – Distribution of the stresses along the circumference (a) at intrados and (b) at extrados

In addition to these measurements, the gallery lining was visually inspected and all cracks observed on the surface of the concrete segments were mapped (Figure 12). This allowed to identify those zones in the gallery that required more frequent monitoring. The misalignments or offset between two consecutive segments were also measured for all rings. It turned out that no new movements were detected since 2014 when these misalignments were last measured. To validate this analysis, a direct measurement of the stress was performed using a stress release technique on one segment of the gallery. This was done by CEREMA (Centre de Recherche des Matériaux in Lille, France) in November 2022 and the outcome of the test is expected in early 2023. This will make it possible to compare the stresses that are calculated from the strains measured in the segment to a direct stress measurement.

Figure 12 – Cracks on the surface of the concrete lining segments of the Connecting gallery

Finally, a PhD was conducted between 2018 and 2022 to examine the viscoplastic behaviour of the Boom Clay. This will improve the understanding of the clay's long-term behaviour and contribute to defining a constitutive law of the clay behaviour. With such a constitutive law, a finite element model can be developed to model the long-term interaction between the Boom Clay and the concrete lining.

## 3.2. In-situ state of stress at the level of the HADES URL – a state of the art

The main objective of this work is to provide a comprehensive summary of the available data on the in-situ stress in the Boom Clay around the HADES URL. In 2022, data from an in-situ dilatometer test were analysed and compared with the outcomes of other in-situ stress measurements performed in the HADES URL. The dilatometer test set-up was installed in November 2008 in an uncased borehole CG26E located close to and nearly parallel to the PRACLAY gallery. The test provides data on the deformation characteristics, stress-strain properties and strength properties of the clay formation.

The measurements of the dilatometer test since its installation are shown in Figure 13. After 14 years, the system is still working. There are two periods during which no data were collected: a 2-year period shortly after the start of the test and a 5-month period in 2021. The data, however, follow a clear trend and the missing data do not hinder the overall interpretation of the test.

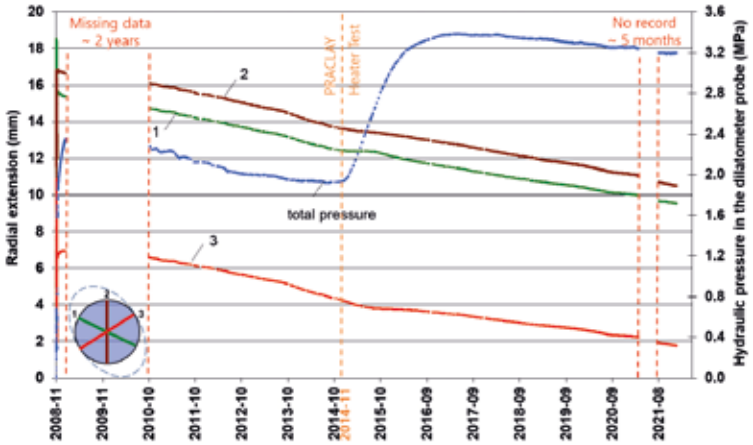



Figure 13 – Total pressure (blue curve) and displacement (red, green and purple curves) measurements obtained from the dilatometer test in borehole CG26E

After installing the dilatometer, the pressures and displacements decrease until the start of the PRACLAY Heater test. Then an almost instantaneous increase in pressure can be observed, reaching up to 3.4 MPa. Initially, the displacements also increase slightly once the heater is switched on, but this increase is only short-lived and the displacements quickly start to decrease again. The rate of decrease is, however, lower than before the start of the heater test.

The decreasing displacements mean that the borehole is contracting. This contraction is not the same in all directions indicating an ovalisation of the borehole. This phenomenon was also observed by other measurements performed in the HADES URL, for example by the strain gauges in the Connecting gallery.

Apart from the dilatometer test, other in-situ stress measurement campaigns have been carried out in the URL, including a Self-Boring Pressuremeter (SBP), High Pressure Dilatometer (HPD), and Hydro-Fracturing (HF). A report is in preparation in which all these measurements are compiled in order to arrive at a more comprehensive and consistent picture of the in-situ stress state of the Boom Clay around the HADES URL. This state of the art report will first describe the methods and techniques used in the HADES URL to determine the in-situ stress. Subsequently, the measurements obtained from these techniques will be presented, together with relevant in-situ mechanical properties for the Boom Clay at the level of the HADES URL. A conclusion that can already been drawn from the analysis performed so far is that the limitations of the applied measurement techniques make it difficult to arrive at a unique value for the in-situ stress around the HADES URL.

## 3.3. Transferability of the geomechanical parameters of Boom Clay around the HADES URL to other locations and depths

The in-situ and laboratory tests performed with samples from the HADES URL examine the Boom Clay behaviour at a depth of 225 m. Today, no site or host rock has been selected in Belgium for the geological disposal of radioactive waste. This also means that even if Boom Clay were selected as the host rock, the disposal site and depth may differ from that of the HADES URL. This raises the question to what extent the characteristics of Boom Clay around the HADES URL are representative of the clay at other locations and depths.

To answer this question, a new study was launched in 2021. Its aim was to first collect the existing experimental results obtained from the Boom Clay at other locations and/or depths and then compare these results with those obtained around HADES.

The literature study showed that few studies have been carried out to characterise the Boom Clay at other locations and depths. Examples are the TRUCK II project which used samples from boreholes in Essen and Mol, at the same depth as the HADES URL, and boreholes in Doel (69 m), Zoersel (120 m), Weelde (313 m) and Blija (455 m, Netherlands) (see Figure 14). Based on these results, it was verified to what extent knowledge about the mechanical behaviour of Boom Clay could be transferred to other depths.

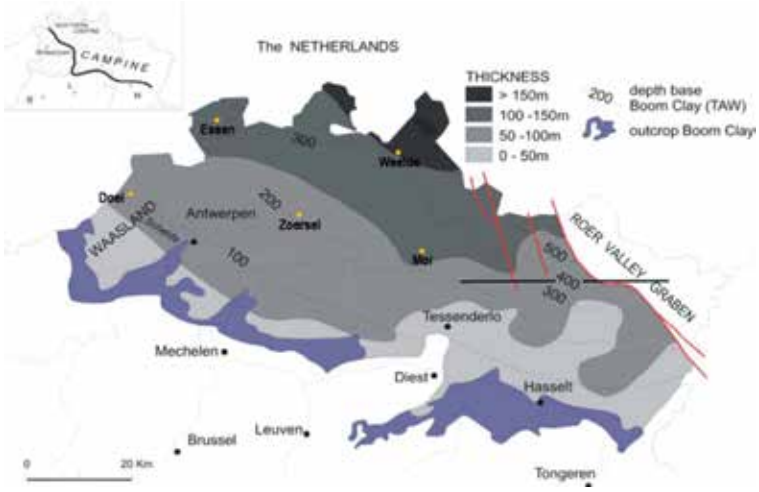



Figure 14 – Locations of the HADES URL in Mol and the boreholes in Doel, Essen, Weelde and Zoersel

The study focused on the geomechanical parameters. The preliminary conclusion is that the transferability of findings from these different studies is a complex issue. On the one hand, many factors intrinsic to the clay, such as its mineralogy, pore chemistry or the loading history to which the clay was subjected, can affect the geomechanical properties of the Boom Clay. On the other hand, there are experimental factors, such as the experimental procedure or the condition of the samples, that can influence the test results. Nevertheless, the study provided a first insight into the extent to which knowledge about the mechanical behaviour of Boom Clay could be transferred to other depths and locations.

This led to the conclusion that Boom Clay characteristics derived at a given depth may prove unreliable when used to characterise the clay at a different depth. Characterising Boom Clay at a depth other than the depth of the HADES URL requires a new experimental campaign. Furthermore, some previous studies mainly focused on the isotropic behaviour of the clay, while Boom Clay shows anisotropic behaviour. A future experimental campaign should therefore study the clay in different directions. The characterisation of Boom Clay would also benefit from using a characterisation protocol that is used for at all depths and locations.

## 4. Instrumentation & Monitoring

Since construction work began on the HADES URL 40 years ago, monitoring has been a key activity. It is an essential aspect of the many field test set-ups and demonstration tests. It played an important role during the construction of the HADES URL and is continuously used for assessing the stability of the underground infrastructure. As a result, over the past four decades, we have gained considerable expertise in monitoring and the associated instrumentation.

The sheer number of sensors already installed requires an appropriate system for record-keeping and maintenance. The sensors deployed in the HADES URL also provide us with a wealth of information on their performance in repository-like conditions. This will be very useful in future applications, which could include more advanced demonstration tests, instrumentation of pilot facilities, or actual repository monitoring. The latter is also an important research topic in its own right, as monitoring is considered an essential component in the development of geological repositories.

## 4.1. Operational work (inventory, maintenance, calibration, etc.)

Streamlining the management of the installed sensors and associated instrumentation (such as data acquisition systems) continued in 2021 and 2022. Steps have been taken to gradually switch from the current data management tool to a platform called LabTool. This fits in the broader goal of developing a complete scientific and technical inventory of the HADES URL. The transition to the new system will, however, take time as there are several thousand sensors installed in the HADES URL.

Together with the LabTool project, a strategic vision was developed on the entire measurement process applied by the EIG EURIDICE. The goal is to develop an integrated set of procedures for all steps in the measurement process, from designing the instrumentation plan and data generation through to the delivery of validated data. This will improve the efficiency and effectiveness of existing and upcoming monitoring projects. This strategy is currently being implemented by reviewing existing procedures, such as those related to calibration and maintenance, inventory management using LabTool, procurement of sensors, and, where necessary, developing new ones.

Furthermore, the ICT department of SCK CEN improved the network through which the instrumentation system can be accessed. This included increasing cybersecurity and improving the way data is acquired, making it easier to detect and fix network errors.

Finally, the yearly calibration of the 297 pressure transmitters in the PRACLAY and ATLAS test set-ups was successfully completed in 2021 and 2022. No problems were reported. Previous calibration efforts revealed that there was no significant drift over a period of a year. It was therefore decided to reduce the calibration frequency to once every two years. From next year, the pressure transmitters in the Connecting gallery will be calibrated one year and those in the PRACLAY Gallery will be calibrated the next. This will reduce the work load while maintaining the necessary skills and expertise to perform these operations. It is also proposed to automate this process. The feasibility of this proposal will be examined in 2023.

## 4.2. Sensor performance assessment

Since construction work on the HADES URL began in the early 1980s, many experimental set-ups of different sizes and for various purposes have been implemented in the various galleries of the HADES URL. 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 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 the monitoring set-ups used in the HADES URL.

A first study, initiated in 2015 and concluded in 2018, dealt with the performance assessment of the instrumentation installed as part of the CLIPEX project. Based on this study, a paper titled *"Assessment of instrumentation performance in the context of geological radwaste disposal – a first case study in the Belgian URL HADES"* has been published (Verstricht et al., 2021)

A second study looked at the PRACLAY in-situ experimental set-up. It started in 2018 and followed the same methodology as developed for the experimental set-up of the CLIPEX project: by assessing the measurement performance of each individual sensor, those factors that affect or contribute to a successful set-up can be derived. Examples of such factors are the sensor technology used, how and in what environment the sensors were installed and what their accuracy and representativeness is.

The PRACLAY set-up contains more than 1300 sensors, which were grouped into 33 so-called "sensor sets". Each sensor set contains similar sensors (same technology and implementation) installed under similar conditions. The study started by explaining the assessment methodology for each sensor set and outlining the historical context. The assessment consists of evaluating each individual sensor against a number of indicators. The five main categories of indicators defined for the first study (i.e., the assessment of the CLIPEX project) were again applied. These categories are described in the following table.

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

The corresponding assessment section of the report contains the contextual information on these indicator results, additional analyses depending on the sensor type and the available data, and conclusions on the performance in the PRACLAY set-up, together with the potential of the sensor technology for future applications. The large number of sensors also made it possible to obtain statistical information about the performance of the sensors, such as their life expectancy and the impact of environmental conditions, such as the temperature and water pressure. The yearly calibration of the sensors also provides a lot of information about the accuracy and drift of the sensors.

The specific nature of the PRACLAY set-up, with a significant part of the instrumentation installed in or around the heated and saturated gallery, with high water pressures (up to 28 bar) and temperatures (slightly above 80 °C), results in harsh conditions for many sensors. This caused many sensors to fail. These conditions, however, provide useful information on the reliability, representativeness and added value of the sensor measurements under elevated temperature and pore water pressure conditions. Valuable lessons can be drawn regarding designing future monitoring plans, of other large-scale tests to an actual repository for radioactive waste disposal. The study was documented in an EURIDICE report (ref. EURIDICE/49029562) that was published in 2022: "*PRACLAY Instrumentation Assessment – Review and performance assessment of monitoring technologies used in the PRACLAY Instrumentation set-up*".

After completing the PRACLAY study, the same methodology was applied to assess the performance of the sensors of the ATLAS test set-up. This set-up consists of six instrumented boreholes (Figure 15), the first three of which were installed in 1992. This means that for some of these sensors the performance can be assessed over 3 decades. Unlike the PRACLAY set-up with over 1300 sensors, the ATLAS set-up was smaller with 87 sensors. This study was completed at the end of 2022 with the publication of the related report (ref. EURIDICE-R-8793) titled "*ATLAS sensor performance assessment*".

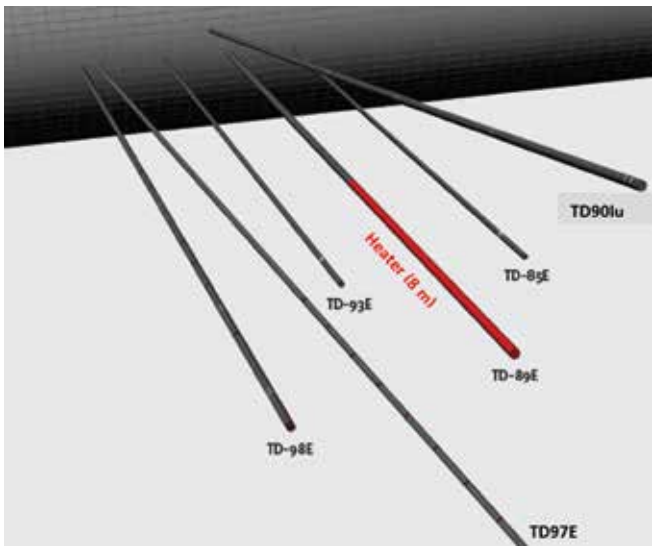



Figure 15 – The ATLAS set-up consists of a heater borehole (heater indicated in red colour) and five monitoring boreholes

In the coming years, the performance of other instrumentation set-ups installed in the HADES URL will also be assessed. Some of these sensors were installed 30 to 40 years ago, providing the opportunity to evaluate sensor performance over a long period of time.

### 4.3. Contribution to WP7 of the EC project PREDIS: Innovations in cemented waste handling and pre-disposal storage

With the monitoring competences present within EURIDICE, our monitoring team also contributed to the design and implementation of the monitoring set-up of four concreted barrels investigating the ASR (alkali-silica reactions) in cemented waste forms in the context of WP7 of the PREDIS project. The set-up itself was installed at the premises of EURIDICE in November 2022, and will run for 2 years.

## 5. International activities

EURIDICE participates in various international activities, including projects of the International Atomic Energy Agency (IAEA) and the European Joint Program on Radioactive Waste Management and Disposal (EURAD). These activities contribute to the preservation of the scientific knowledge that has been built up over the past 40 years and increase the international visibility of the RD&D performed at the HADES URL. They also allow to exchange information and experiences with other geological disposal programmes and to learn from these experiences abroad. In addition, EURIDICE also contributes to the CI (Cement-Clay Interaction) test in the Mont Terri URL in Switzerland.

### 5.1. International Atomic Energy Agency – 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 for Geological Disposal*" is being developed by the IAEA and planned to be published in 2024. The compendium will provide an overview of the vast amount of knowledge accumulated from RD&D conducted in underground laboratories worldwide over the past 60 years. It will include references to more in-depth information and reports on specific RD&D results. This will help readers with an interest in some specific experiments or RD&D efforts to find more detailed information.

The IAEA invited EIG EURIDICE to provide input related to the RD&D conducted in the HADES URL over the past 40 years. With the support of SCK CEN's W&D expert group, EURIDICE provided a description of the history and design of the HADES URL, together with an overview of more than 30 experiments conducted in the HADES URL. This overview included the background, objectives, set-up and key findings of each experiment and a list of references. EIG EURIDICE has also been involved in the reviewing of the overall IAEA report.

Furthermore, EURIDICE regularly participates to IAEA URF Network meetings. This is a network of organisations and institutes involved in the RD&D of geological disposal. URF Network meetings were held in 2021 and 2022 providing an opportunity to present work done by EURIDICE and learn about progress made in other programmes.

### 5.2. European Joint Programme on Radioactive Waste Management and Disposal – EURAD

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

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

**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

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

For Task 2.3, EURIDICE provided support in writing the benchmark exercise. This exercise is divided into two steps. First, a generic case was modelled for the three host clay/claystone formations: Boom Clay, Opalinus claystone and Callovo-oxfordian claystone. This was completed in early 2022. In a second step, an in-situ heater test was modelled in each of the three underground research laboratories in Bure (France), in Mol (Belgium) or in Mont-Terri (Switzerland). EURIDICE provided input for modelling the large-scale PRACLAY Heater test. Since May 2022, EURIDICE/SCK CEN has been contributing to the modelling of this benchmark, together with UPC (Barcelona), ULiège (Belgium) and BGE (Germany).

The benchmark activities will be completed in November 2023 resulting in a summary of the modelling results and comparisons the modelling of the PRACLAY Heater test by other teams. This is an opportunity to see if more advanced constitutive laws can result in a better understanding of the test outcomes.

**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 the HADES URL to assess the possibility of re-using existing experimental set-ups, MEGAS has been chosen for this long-term in-situ gas diffusion experiment which is now named NEMESIS. 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.

In 2021 and 2022, EURIDICE has been supporting the W&D expert group in installing the experimental set-up in the HADES URL and conducting several in-diffusion tests. This also included some small tests at the HADES URL and the EURIDICE workplace at the surface to get more insight in some specific processes, such as Darcian flow under small pressure gradient and pressure head loss in microtubes. Knowledge about these processes is necessary to control and interpret the in-diffusion tests and the long-term gas diffusion tests. In the following 2 years of the project, the experimental results will be analysed.

**WP MODATS – MONITORING EQUIPMENT AND DATA TREATMENT FOR SAFE REPOSITORY OPERATION AND STAGED CLOSURE**

EURIDICE joined about 30 other organisations in preparing and implementing the proposal for the MODATS Work Package. This project started on 1 June 2021 for a period of 3 years. It contains two main technical tasks: one is dedicated to data management in the context of a geological repository and another relates to the continuation of the MoDeRn and Modern2020 projects on sensor technology development.

EURIDICE is involved in the task on data management and carried out the following activities in 2021 and 2022:

- Contribution to the URL survey to map data management practices in field experiments. EURIDICE completed three surveys, covering the PRACLAY, ATLAS and CLIPEX experiments.
- Development of guidelines for QAPP's (Quality Assurance Project Plans) providing guidance for the data (and general project) management of field monitoring set-ups. This subtask will continue into 2023 and has started with the analyse of current practices in the different set-ups.
- Preparation of a data-set of PRACLAY, which is one of the five so-called "MODATS reference experiments" (together with other monitoring set-ups in Bure (France), Mont Terri (Switzerland), Onkalo (Finland) and Äspö (Sweden).

The project will result in a synthesis of lessons learnt from URL experiments and guidance on quality assurance guidelines related to repository monitoring. This will, in turn, lead to greater confidence in our abilities to monitor an underground repository.

**WP MAGIC – CHEMO-MECHANICAL AGING OF CEMENTITIOUS MATERIALS UNDER COUPLED DISTURBANCES BASED ON A MULTISCALE APPROACH**

One of the objectives of the WP MAGIC is to quantify the chemo-mechanical multi-scale evolution of cementitious materials as they degrade over time in a disposal facility. Combined leaching and carbonation are the main degradation processes considered. The experimental work will mainly be carried out by SCK CEN in collaboration with the laboratory of LAMCUBE (CNRS) from France. EURIDICE supports the interpretation of the macro-scale mechanical tests on the chemically degraded concrete samples. So far, these mechanical tests have not yet begun.

## 5.3. CI test in Mont Terri – modelling of swelling pressure evolution

The CI (Cement-Clay Interaction) test has been running for 15 years in Mont Terri URL with the objective to study the long-term interaction between cementitious materials, bentonite and host clay. The large number of sampling results and swelling pressure measurements at the interfaces resulted in some interesting observations.

SCK CEN and EURIDICE are interested in the numerical modelling of CI test, especially in "Aim 2" related to linking chemico-physical evolution to the evolution of swelling pressures in the interface region.

A step-by-step approach is being taken to numerically interpret the observations. The modelling work first focuses on the macrostructure of bentonite to capture the short-term evolution of the swelling pressure when the bentonite is unsaturated. This allows deriving a set of macrostructural parameter values which can be used to interpret the next steps. Then the effect of the microstructure and its interaction with the macrostructure on the swelling pressure are examined. These effects are essential to interpret the long-term swelling pressure and to characterize the micro- and macrostructure of the bentonite. Finally, an exploratory study is carried out to explicitly take into account the long-term impact of chemicals on the swelling pressure of saturated bentonite in a simplified manner.

# 6. PhD programme

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

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

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

In 2017 Saeid Babaei started this PhD research which was funded by SCK CEN and is being conducted in collaboration with the Antwerp University. The PhD was successfully defended in April 2021. The goal of the research was to investigate the THM behaviour of cementitious engineered barriers, in particular, the barrier for high-level radioactive waste containers considered in the Belgian geological disposal programme. The research modelled the microstructure of the material based on its chemical composition and reaction condition (curing, age, temperature, etc.). This microstructure was used to numerically derive the THM properties of the material. These properties were used in THM simulations assessing the hydro-mechanical behaviour of the engineered barrier. For example, a drying shrinkage process was modelled to evaluate the impact of this process on the long-term performance of concrete structures.

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

This PhD is co-funded by ONDRAF/NIRAS and SCK CEN and is a joint collaboration with the "Laboratoire Navier/CERMES, l'École des Ponts ParisTech". The project was awarded to May Awarkeh, who started the research in October 2018 and completed it in November 2022.The need for this research stemmed from the fact that although many studies have been conducted to understand the long-term behaviour of the Boom Clay, there are still some knowledge gaps. Examples are the gallery convergence during construction and the long-term interface behaviour between the Boom Clay and the galleries. The work resulted in a elasto-viscoplastic model capable of describing various viscoplastic behaviours, including rate effects and drained creep. The good agreement between simulations and experimental results demonstrated the good performance of the model.

## 6.3. Reduced Order Modelling Technique for Coupled Geomechanics Problems

This research project was initiated at the "Université libre de Bruxelles" (ULB) and the "Universitat Politècnica de Catalunya" (BarcelonaTech, UPC) in 2017. It was funded through a European Erasmus Mundus Joint Doctorate Programme for the first three years. The final year (2021) was funded by SCK CEN. This project was awarded to Ygee Larion who successfully defended it on 1 February 2022. The student developed a Reduced Order Model (ROM) to numerically simulate the ATLAS III Heater test. Numerically modelling complex such THM coupling problems in soils can require long calculation times. By using a ROM, the computational cost can be significantly reduced. ROM is a simplified and reliable model that preserves both the essential behaviour and the dominant effects inherent to the problem. ROM is widely used in aerodynamics, network systems, fluid dynamics, etc., but its application for solving coupled THM problem is rare. The ROM model developed by Ygee Larion reduced the computational time to model the ATLAS III Heater test by one to two orders of magnitude compared to finite element methods (FEM). Nevertheless, there is excellent agreement between the FEM and ROM calculation results. In the final years of the PhD research (2021-2022), Ygee developed a ROM for the PRACLAY Heater test taking into account the elastoplastic behaviour of the Boom Clay. The knowledge of this PhD work was transferred to SCK/EURIDICE and will be further applied and developed.

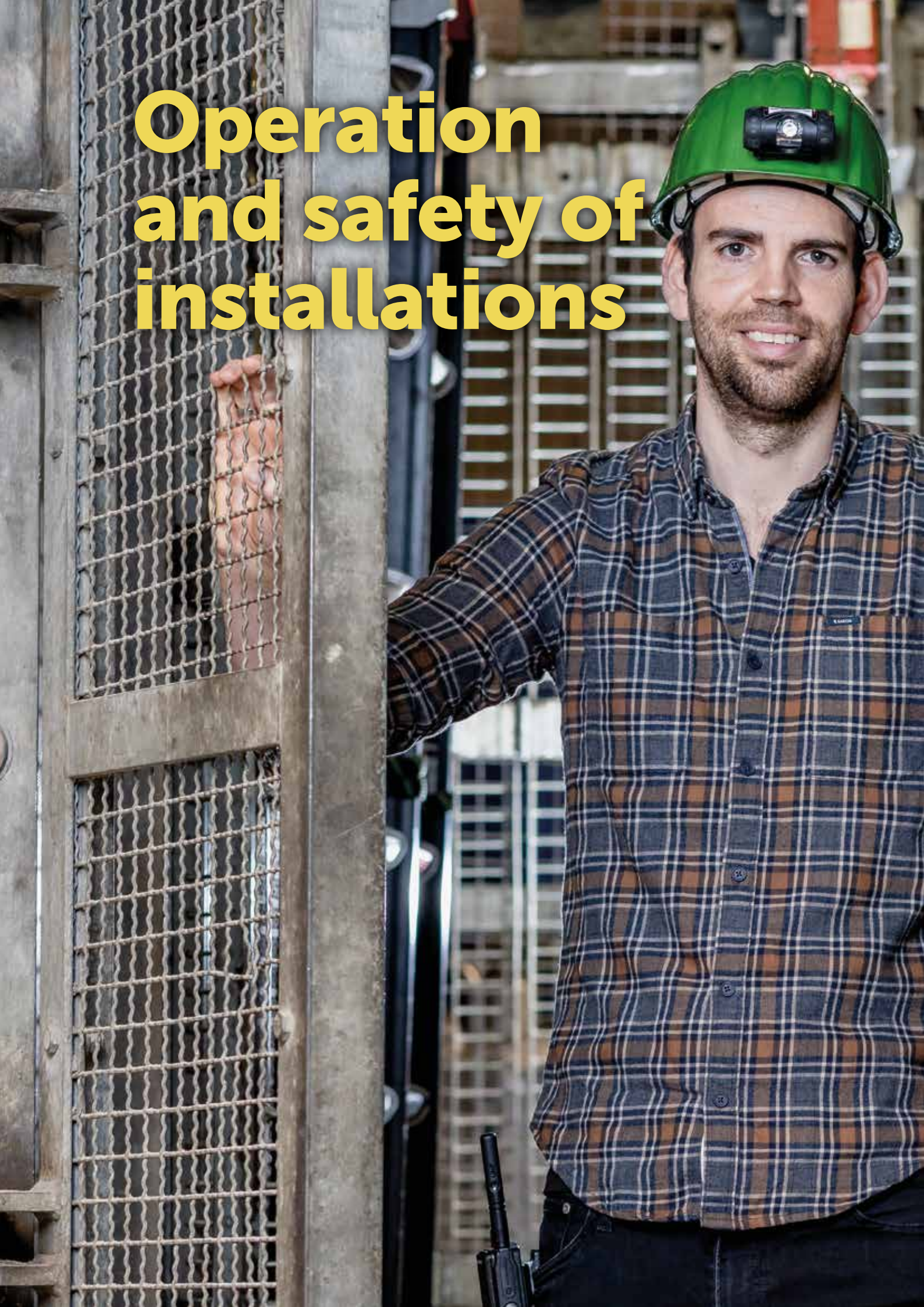
## 6.4. Investigation of the effect of the pore fluid chemistry on the hydro-mechanical behaviour of Boom Clay (C-H-M coupling behaviour of Boom Clay)

This PhD is funded by SCK CEN and is a joint collaboration with the "Laboratoire Navier/CERMES, l'École des Ponts ParisTech". It was awarded to Hassan Al Maïs who started the research work in October 2021. The goal is to examine the effect of a saline solution on the HM behaviour of Boom Clay. The inventory of long-lived wastes in Belgium contains bituminised waste. When this waste is placed in a geological disposal facility, it will come into contact with infiltrating groundwater once the waste packages are breached. The large amounts of highly soluble NaNO3 present in the waste will dissolve and diffuse into the host formation. The research consists of a laboratory experimental programme to examine the effect of solutions with different salt concentrations and sodium occupancies on the behaviour of Boom Clay. Based on these results, a new constitutive model will be developed taking into account the chemical perturbation. This model will be implemented into LAGAMINE, a finite element code. This code is developed by the University of Liège where the numerical work will be done.

## 6.5. Evolution of transport, microstructural and hygro-mechanical properties of cementitious materials subjected to coupled chemical degradation via a multiscale approach

This project was awarded to Mr Tang Mingzhe in 2022 by the SCK CEN Academy and will be financed jointly by SCK CEN and ONDRAF/NIRAS. The project will be undertaken within the "Laboratoire de mécanique multiphysique multiéchelle" (LaMcube) at the University of Lille and the Department of Structural Engineering and Building Materials at the University of Ghent. The work will start at the beginning of 2023.

# Operation and safety of installations



The Statutory Rules define the responsibilities and tasks of EIG EURIDICE concerning the management and operation of the installations on the land for which EIG EURIDICE holds a building lease. The activities of EIG EURIDICE are regulated by the following licenses:

- operating license for underground activities
- environmental license
- license as a nuclear facility class II

In recent years, there have been several changes to the infrastructure. The most important one is the refurbishment of the first shaft to the HADES URL in 2020 and 2021. Smaller changes include the removal of cooling installations and the dismantling of several storage units. These changes required the operating license to be renewed. The licence application was prepared with the Federal Public Service for Employment, Labour and Social Dialogue and with the community of Mol. In May 2021, the licence was granted by the community of Mol. This licence is valid for the next 20 years.

These changes also required an update of the environmental license. A new environmental licence application was prepared incorporating the changes to the infrastructure and an update of the environmental inventories. The licence was granted in August 2022 and is valid until October 2033.

The previous nuclear licence of EIG EURIDICE was valid until the end of 2021. Therefore, an application for a new nuclear licence was submitted to the Federal Agency for Nuclear Control and in August 2021 a new nuclear licence was granted for 15 years, until 2036.

The primary task of the Operations and Safety team is to maintain the HADES URL and its above-ground facilities, in order to keep the URL operational and available for researchers and visitors. Secondly, the Operation and Safety team must ensure the health and safety of employees, visitors and external parties at all times. As far as these tasks are concerned, the following activities were conducted in 2021-2022.

## 1. Electrical installations

The main general legal requirements for electrical installations in Belgium are specified in the AREI[2] regulations. In order to comply with these regulations, a number of outdated electrical cabinets were replaced in 2021 (Figure 16a). The commissioning works for the new electrical cabinets started in 2022 and are expected to be completed early 2023. All electrical installations of EIG EURIDICE will then have the necessary certificates to administratively comply with the applicable technical regulations.

The site of EURIDICE is electrically connected to the site of SCK CEN. Because SCK CEN renewed the main electrical connection and converted it from 10kV to 15kV, new transformers were purchased (Figure 16b). This guarantees the power supply to the hoisting system of shaft 1 and the oldest section of the HADES URL. This conversion was completed in 2022.

(a)

(b)

Figure 16 – (a) New electrical cabinets and (b) transformers

## 2. Data network and data acquisition system

The data network and the associated data acquisition system in the HADES URL and the above-ground facilities are key for the research activities at EURIDICE. In 2020, work began on reconfiguring and optimising the entire network system to increase its security and reliability. Due to the complexity of the scientific experiments in the HADES URL, the work could only be completed in 2021.

[2] Algemeen Reglement op de Elektrische Installaties (in English: General Regulations on Electrical Installations)

## 3. Technical support for RD&D

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

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

## 4. Inspections, checks and periodic maintenance

Periodic inspections and preventive maintenance are required to ensure the safety of employees and visitors on the site. These include daily, weekly, monthly, quarterly, semi-annual and annual checks and inspections by EURIDICE technicians and AIB Vinçotte.

Due to the lack of national regulations regarding the construction and refurbishment of shafts in underground mine-type facilities in Belgium, the refurbishment of shaft 1 was carried out according to German regulations (BVOS/TAS). To ensure the continued safe operation of the site in the absence of such regulations, EIG EURIDICE developed a new inspection and control programme for its entire infrastructure. This programme is based on German regulations and EURIDICE's own experience and expertise in inspecting and maintaining the underground infrastructure. A lesson from this project is that the lack of national regulations for this type of activity can be a major disadvantage for the design and construction of a future geological disposal facility in Belgium.

## 5. Safety on site

The OC VGMB (Consultation Committee on Safety, Health, Environment and Security) meets monthly. The director of EURIDICE, the Team Manager EURIDICE, the Operations & Safety Manager EURIDICE, the prevention officers of SCK CEN and the safety coordinator of ONDRAF/NIRAS discuss the general safety issues of the activities at EURIDCE. The Operations & Safety Manager provides an overview at each meeting of the non-conformities and planned or on-going actions.

## 6. Fire detection system

Following a small fire incident in an electrical cabinet in the demo hall in 2021 and the subsequent investigation which showed that the lack of fire detectors in the demo hall played a major role in the late detection of this fire, the fire detection system was re-evaluated. This led to an optimisation of the system in 2022. Additional fire detectors have been placed in the demo hall and the office spaces. Furthermore, automatic gas valves have been installed in the boiler rooms and were connected to the existing gas detection and fire control panel (Figure 17).

Figure 17 – Automatic gas valve connected to the existing gas detection and fire control panel

# 7. Refurbishment of shaft 1

The refurbishment of shaft 1, the oldest access shaft to the HADES URL that was constructed in 1980 (Figure 18), was finally completed in 2021. The preparations for this refurbishment date back to 2011 when EURIDICE decided to investigate the possibility of renewing the shaft's hoisting system. This long preparation period was necessary due to the complexity of the project.

The lack of national building codes and regulations for the construction and operation of underground mine-type facilities in Belgium made it difficult to specify the requirements for the shaft refurbishment works. After consultation with the national safety authorities (the Belgian Federal Public Service for Employment, Labour and Social Dialogue), it was agreed to follow the requirements from the German BVOS/TAS regulations which are considered state-of-the-art.

Figure 18 – Hoisting tower and machine room of the old hoisting system of shaft 1

In 2017, a consortium of Tractebel and DBE (Germany) was contracted to support EURIDICE in developing the preliminary design and in defining the technical specifications for the new hoisting system and associated components. The engineering company Tractebel also assessed the stability and watertightness of the shaft lining (Figure 19). The stability of the shaft has been confirmed for a period of at least 20 years and a programme has been prepared for injecting leaking cracks in the lining during the refurbishment works.

Figure 19 – Cracks in the lining of shaft 1 through which limited amounts of water enter the shaft

The design studies were completed in 2018. The cost of the project, which is entirely financed by ONDRAF/NIRAS, was estimated at approximately 7 million euro. In 2019, the building and environmental permit for the works was granted and after a public tendering procedure, contracts were awarded to Swinnen NV from Balen, Spie Belgium from Geel and the German company Thyssen Schachtbau.

The works on site finally started in early 2020. The refurbishment operation comprised seven steps which are illustrated and explained in Figure 20. The entire access infrastructure of the oldest shaft, with its iconic green tower and hoist installation, was completely dismantled after 40 years of service (Figure 21).

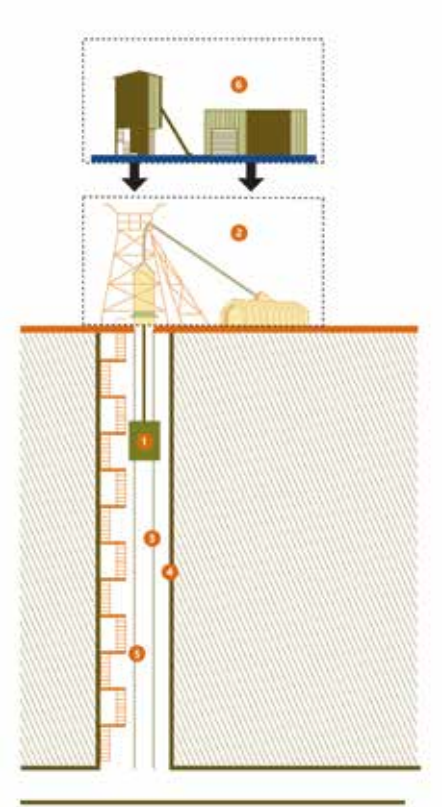


Figure 20 – Refurbishment of shaft 1 in seven steps.
Step 1: Removing the hoisting cage and cable; Step 2: Demolishing the tower; Step 3: Dismantling the shaft;
Step 4: Repairing the concrete lining; Step 5: New piping in the shaft; Step 6: New hoisting building; Step 7: Installing the hoisting system

(a) (b)

Figure 21 – (a) The iconic green tower and (b) the hoisting system were dismantled after 40 years of service

The shaft lining was cleaned, thoroughly inspected and repaired at more than 20 locations. The main and emergency cages were installed along with new guide rails. Also the electrical and data cables, pipes for compressed air and high-pressure water pipes, and the ventilation duct were renewed. The small diameter (2,65m), the curvature of the shaft and the requirement to comply with the safety distances between the components as defined in the BVOS/TAS regulations, made installing these components challenging. To carry out the work in the shaft, a temporary hoisting system was used to lower a narrow cage with the workers to an adjustable platform in the shaft (Figure 22).

(a) (b)

Figure 22 – (a) The shaft's small diameter (2,65m) and curvature complicated the works inside the shaft; (b) a temporary, narrow cage was used to transport workers down the shaft

Due to COVID-19 restrictions, the works in the shaft were temporarily suspended in the spring of 2020. The initial goal of having the new hoisting system operational by the end of 2020 was therefore no longer feasible. However, in 2021 all critical infrastructure, including the hoisting tower, the main and emergency hoisting systems and the cages were installed (Figure 23).

(a) (b)

Figure 23 – (a) The new hoisting tower and hall with the above-ground components of the hoisting system, and (b) the drum winders of the main and emergency cage

After the installation of the complete infrastructure, all functions were tested. A BVOS/TAS conformity certificate was issued by German accredited experts of DMT. The provisional delivery of the works was done at the end of 2021. The final delivery will take place at the end of 2023.

Despite the significant risks of working in a deep shaft and in a very tight space, no accidents or incidents occurred during the works. The works were also delivered within the planned budget of 7 million euro. With this major renovation, EURIDICE ensures the accessibility of the HADES URL for the coming decades. Because of the scope and importance of this project for EURIDICE and the Belgian disposal programme, an evaluation of all aspects of the project was conducted to draw a series of lessons learnt.

In October 2021 there was a festive opening by the directors of EIG EURIDICE, ONDRAF/NIRAS and SCK CEN. A video about the new shaft infrastructure can be found on the EURIDICE website: https://www.euridice.be/en/content/shaft-1-reopened-after-renovation

# 8. Qualifications of the appointed responsible staff

The safe operation of the HADES URL requires qualified personnel to operate the hoisting system, conduct inspections and checks and guide staff and visitors to the underground laboratory. The qualifications of the personnel performing these tasks have been defined and implemented in SCK CEN's learning and development tool CONNECT, together with the training they need.

The following personnel are qualified to guide employees and visitors in the HADES URL:

- 5 EURIDICE employees are fully qualified to conduct visits and operate the installation
- 5 EURIDICE employees and 2 SCK CEN employees are partially qualified. They can accompany visitors but are not allowed to operate the installation

An annual training is mandatory for all staff who have a role in the safe operation of the HADES URL. In addition, there are two "*operation manuals*". These set out the procedures for operating the technical installations, including a description of the error messages alarms, and the emergency procedures.

# 9. Supporting third-party research

## 9.1. JRC-Geel

The Joint Research Centre (JRC) in Geel is one of several research centres of the European Commission. It develops new measurement methods and tools such as reference materials, and supports more than 300 laboratories in EU Member States. For example, JRC-Geel produces and distributes reference materials for Member States to conduct environmental monitoring.

Some key projects of JRC-Geel in 2021-2022 included:

- characterisation of reference materials for food safety, building materials and nuclear decommissioning
- radiotracer studies of water from the Pacific Ocean to determine ocean mixing, in order to build reliable climate models
- measurement of rare nuclear decays
- measurements of radioactivity induced by cosmic rays in meteorite samples, to determine parameters such as cosmic age, terrestrial age, path through space, original size before break-up, etc.

Since 1992, JRC-Geel leases a part of the HADES URL to perform ultralow-level gamma-ray spectrometry. The HADES URL offers a suitable environment to detect very low amounts of radioactivity because the background radiation due to cosmic rays is significantly lower in the URL than above ground. This enables JTR-Geel to support the European Commission and other institutes in fields such as international standardisation, radioactive waste management and radioprotection. For example, the new international standard on nuclear instrumentation, IEC 61452 (https://webstore.iec.ch/publication/63679), refers to gamma-ray spectra measured in the HADES URL. The contract between EURIDICE and JRC-Geel is a Service Agreement that can be extended on a yearly basis.

## 9.2. Max Planck Institute – the LEGEND project

With the international LEGEND (Large Enriched Ge Experiment for Neutrinoless double beta Decay) partnership, the Max Planck Institute participates in the 21st century's fundamental particle physics research. To conduct this research project, LEGEND looks at the extremely rare natural radioactive decay of 76Ge, arranged in the form of 120 Ge detectors (200 kg in total), at the underground Laboratori Nazionali del Gran Sasso (LNGS) in Italy. Most of these detectors were tested in the HADES URL, where the measurement and storage conditions are ideal to avoid cosmic-ray activation and ensure low background contributions. The measurements were conducted by LEGEND collaborators and the JRC-Geel group (mentioned in the previous section), with the support of the EIG EURIDICE team.

Continuing the successful detector testing campaigns in 2019 and 2020, a further 20 detectors were tested in 2021 and 2022. This resulted in an additional 40 kg of detector mass that was characterised in the HADES URL. This collaboration between LEGEND and EIG EURIDICE will continue in 2023 with the delivery of more Ge detectors.

# Communication

Communication on its activities is one of EURIDICE's statutory tasks. The HADES URL and the above-ground exhibition are powerful tools for explaining the research on geological disposal in poorly indurated clays. A visit to the underground laboratory is the best way for visitors to get an idea about the concept of geological disposal (Figure 24). In addition to arranging visits to the exhibition and the URL, EURIDICE has its own website[3], events and publications to inform a wide audience about its activities within the context of ONDRAF/NIRAS's research programme on geological disposal.

Figure 24 – University students visiting the HADES URL

In 2020 the communication strategy for the coming years was formulated in interaction with both constituent members. EIG EURIDICE focuses more proactively on specific stakeholders for visiting the HADES URL. The goal is to increase the visibility of the research activities in the HADES URL for specific academic stakeholders linked with EURIDICE's fields of expertise, and for interest groups involved in the decision-making process on the long-term management of high-level and/or long-lived waste. In addition, all communication activities will be brought in line with the communication strategy of both constituent members through Tabloo, a new communication centre which opened in 2022 in Dessel.

## 1. Visits

Since its opening in 2022, Tabloo is a starting point for all communication on radioactive waste management and nuclear research at SCK CEN for stakeholders that visit the HADES URL. While Tabloo is the main communication tool, also focussing on the general public and young people, EURIDICE now focuses on technical-scientific visits and visits for specific stakeholders, such as those directly or indirectly involved in the decision-making process for geological disposal.

During part of 2021 and 2022, underground visits were not possible because of the refurbishment of shaft 1 and the Covid-19 pandemic. In total, 422 visitors were still welcomed in 2021 and 1025 in 2022 (in the years before EURIDICE welcomed more than 2000 visitors per year). Among these visitors were federal ministers, governmental employees and foreign ambassadors.

## 2. 40 years of HADES

Construction of the HADES URL started in 1980, with the first shaft excavated between 1980 and 1982, and the first gallery constructed 1983-1984. This means that the HADES URL celebrated its 40th anniversary between 2020 and 2022. EURIDICE, ONDRAF/NIRAS and SCK CEN wanted to mark this occasion with the goal of increasing the visibility of EURIDICE and the HADES URL by putting the spotlight on the achievements of 40 years of research and development.

[3] https://www.euridice.be/en

Therefore, a social media campaign was launched and a VIP event and a scientific exchange meeting were organised. During the exchange meeting some key scientific and technological achievements from 40 years research in the HADES URL were highlighted. Finally, a special issue journal of the Geological Society London was published presenting the main contributions of the HADES URL to both national and international research into geological disposal.

## 2.1. Social media campaign and public outreach

The anniversary of HADES offered an opportunity to increase the visibility and public knowledge about the RD&D on geological disposal. Therefore, a social media campaign was launched. This included advertising on Facebook and Instagram and the creation of a webpage www.HADES40.be containing key information about HADES and the Belgian RD&D programme on geological disposal.

The webpage also contains podcasts introducing the listener to the little-known but fascinating topic of geological disposal (Figure 25), and videos in which scientists provide answers to frequently asked questions (Figure 26).


Figure 25 – Podcasts about geological disposal (in Dutch and French) on the HADES40.be webpage


Figure 26 – Videos (in Dutch and French) answering frequently asked questions about geological disposal on the HADES40.be webpage

This social media campaign ran from July to October 2022. At the end of the campaign, data were collected about the number of people the campaign had reached.

| **Region** | **People reached** |
|---|---|
| Brussels | 15.037 |
| Flanders | 156.380 |
| Wallonia | 78.318 |
| **Age** | **People reached** |
| 18-24 | 16.124 |
| 25-34 | 47.285 |
| 35-44 | 44.086 |
| 45-54 | 48.885 |
| 55-64 | 53.300 |
| 65+ | 40.759 |
| **Gender** | **People reached** |
| Female | 61.490 |
| Male | 186.773 |
| Unknown | 2.175 |

The outreach of the podcasts and videos was large. A survey was done to determine the so-called "*ad recall rate*". This is the number of people who remember seeing the ad when asked about it two days later. This ad recall rate turned out to be high for almost every video and podcast.

Finally, also a Mobile Expo was put together on 40 years research and development in the HADES URL was put together for flexible use at specific events and occasions (Figure 27). This Mobile Expo has been in the entrance hall of Tabloo for several months, but has also been used at events elsewhere as a temporary exhibition, for example at the Nerdland Science Festival in Flanders.

Figure 27 – Mobile expo about 40 years HADES

## 2.2. VIP event

In April 2022, a VIP event was held in Tabloo to celebrate the anniversary. The target audience were people involved in decision-making on geological disposal and people who have a say in the societal debate linked with the decision-making process. The event was attended by 140 guests who were offered a tour through the Tabloo exhibition.

This VIP event was attended in person by the Federal Minister of Energy Tinne Van der Straeten and via video by the Minister of the Economy and Employment Pierre-Yves Dermagne. The Minister also visited the HADES URL and attended the press conference on 40 years HADES together with the Directors-general of SCK CEN and ONDRAF/NIRAS, Erik van Walle and Marc Demarche. At the event, a panel discussion was organised presenting several perspectives on the role of the HADES URL in national and international research into geological disposal and on the way geological disposal can be implemented in Belgium.


(a)

(b)

Figure 28 – (a) Visit of Federal Minister Tinne Van der Straeten to VIP event, and (b) panel discussion about the role of the HADES URL in national and international research,

## 2.3. Special publication and scientific event

Several key contributions of the HADES URL to Belgian and international research into geological disposal were compiled in a Special Publication of the Geological Society London: "*Geological Disposal of Radioactive Waste in Deep Clay Formations: 40 Years of RD&D in the Belgian URL HADES*". The publication of the book is expected by beginning 2023 (see section 1 under the part on the RD&D on the geological disposal of high-level and long-lived radioactive waste).

In December 2022, a scientific exchange meeting was organised during which some of the articles of the Special Publication were presented. The meeting was attended by 125 scientists, academics and people working in the field of geological disposal, both from national and international institutes and organisations.

Figure 29 – HADES40 special exchange meeting, Friday 9 December 2022

## 3. Newsletters

EURIDICE published the following newsletters in 2021:

- Shaft 1 reopened after thorough renovation shaft 1 (December 2021)
- PRACLAY Newsletter #4: Seven years of successful heating at the HADES URL (December 2021)

## 4. Participation in external events, conferences and meetings

In 2021 and 2022, EURIDICE staff participated in the following external events, conferences and meetings:

- IAEA meetings in 2021 and 2022
  - EURIDICE represented Belgium at the IAEA URF Network meetings in 2021 and 2022. The IAEA URF Network forms a practice and learning community for geological disposal. It provides a platform for its members to review and share best practices in developing, evaluating and implementing geological disposal solutions. Emphasis is placed on the role and use of underground laboratories in supporting the developing and implementing these solutions.
  - EURIDICE also attended an IAEA workshop dedicated to data management in 2022. Contributions from NAGRA, ANDRA and CNNC (China) illustrated the challenges and perspectives of long-term data management in the field of geological disposal.
- The European Nuclear Young Generation Forum (ENYGF) (Taragona, Spain, 27-30 September 2021)
  EURIDICE contributed to the European Nuclear Young Generation Forum (ENYGF). This event takes place every two years and brings together European students and young nuclear professionals. The event is organised by the ENS Young Generation Network, in cooperation with the IAEA. The chosen theme for the conference is "Look ahead". Jan Verstricht delivered a presentation titled "Perspectives for long-term repository monitoring - lessons learned from underground research lab demonstrators" as one of three invited speakers for the sub-theme "Management of radioactive waste."
- NEA Clay Club meetings in 2021 and 2022
  Argillaceous media are being considered in many NEA member countries as potential host rocks for the disposal of radioactive waste. In this context, the NEA established an international working group on argillaceous media in 1990, informally known as the "Clay Club". EURIDICE participated to the meetings held in 2021 and 2022.
- NEA-METI online workshop (22 September 2021)
  The NEA and Japan's Ministry of Economy, Trade and Industry (METI) co-organised an online International Workshop on Joint Utilisation of Underground Research Laboratories for Research and Development Projects. The purpose of this workshop was to strengthen and discuss international cooperation in RD&D programmes utilising URLs. EURIDICE participated in the workshop.
- EURIDICE was invited by the Belgian Association for Underground Techniques and Urban Planning ABTUS-BVOTS to participate in a seminar on Underground and Environment on 29 March 2022. Arnaud Dizier gave a presentation on the long-term stability of tunnels in deep clay formation.
- During a field visit by the International Association of Hydrogeologists (IAH) as part of the IAH 2021 conference (8 September 2021), Arnaud Dizier gave an overview of EURIDICE's THM research (*"In-situ THM research on Boom Clay at HADES URL"*) and Jan Verstricht presented challenges and perspectives related tomonitoring (*"Perspectives for long-term repository monitoring - lessons learned from underground research lab demonstrators"*).

- EURIDICE experts were contacted by scientists working on the Einstein Telescope EMR Site & Technology (E-TEST) project. The ultimate goal of this project is to create a world-leading underground laboratory 300 m deep in the Euregion Meuse-Rhine region (near the border between Belgium, the Netherlands and Germany) to detect gravitational waves. In this context, the HADES URL was visited several times, focusing on construction and monitoring technology.
- On 1 June 2022, the "Provinciale Ontwikkelingsmaatschappij Limburg" organised a workshop on Tunnelling and water technology. During this workshop, EURIDICE presented its expertise on excavation and monitoring and offered a visit to the HADES URL.
- EURIDICE scientists presented their work at the 8th International Conference on Clays in Natural and Engineered Barriers for Radioactive Waste Confinement, June 2022, Nancy, France. This Clay Conference provides a unique networking platform for sharing scientific and technological knowledge.

## 5. Media coverage

The events and campaign about 40 years HADES created a lot of media coverage. There was the own reporting on the event:
- press release - HADES blows out 40 underground candles
- article in GLUON 21, SCK CEN's quarterly publication for its employees
- article on ONDRAF/NIRAS' newsletter

Also national media paid attention to the event (Figure 30), such as:
- 2022-04-26 **VTM Nieuws** – 40 jaar nucleair lab onder de grond (vanaf 36'48")
- 2022-04-27 **RTL Info** – Déchets nucléaires: visite d'un laboratoire souterrain à Mol
- 2022-04-27 **Kanaal Z** – Boomse klei ideaal voor berging radioactief afval
- 2022-04-27 **VRT NWS** – Radioactief afval: onderzoek op 200m diep in Boomse klei
- 2022-04-27 **RTV** – Unieke kijk in ondergronds labo in Mol: "Berging radioactief afval nog niet zeker hier"
- 2022-04-27 **Nnieuws.be** – HADES blaast 40 ondergrondse kaarsjes uit : 'Labo op 225m diepte test veiligheid van geologische berging in kleilagen'
- 2022-04-27 **Het Laatste Nieuws** – Is radioactief afval ondergronds bergen een veilige optie? HLN brengt exclusief bezoek aan onderzoekslabo dat 225 meter onder de grond ligt (online)
- 2022-04-28 **La Libre Belgique** – Où va-t-on stocker nos déchets nucléaires ? On avance timidement (online)
- 2022-04-28 **L'Echo** – Un pas de plus vers le stockage géologique des déchets radioactifs (online)
- 2022-04-28 **Gazet van Antwerpen** – Burgers mogen mee beslissen over ondergrondse berging kernafval (online)
- 2022-04-28 **De Tijd** - Ondergrondse berging wordt basisscenario voor kernafval (online)
- 2022-04-28 **Het Laatste Nieuws** - Oudste ondergrondse laboratorium van Europa blaast 40 kaarsjes uit: "Hier is pionierswerk verricht"


Figure 30 – A selection of newspaper articles published on the occasion of 40 years Hades

Furthermore, an article was published in Paris Match4 about the Belgian RD&D on geological disposal. The article featured Maarten Van Geet who was interviewed at the HADES URL.

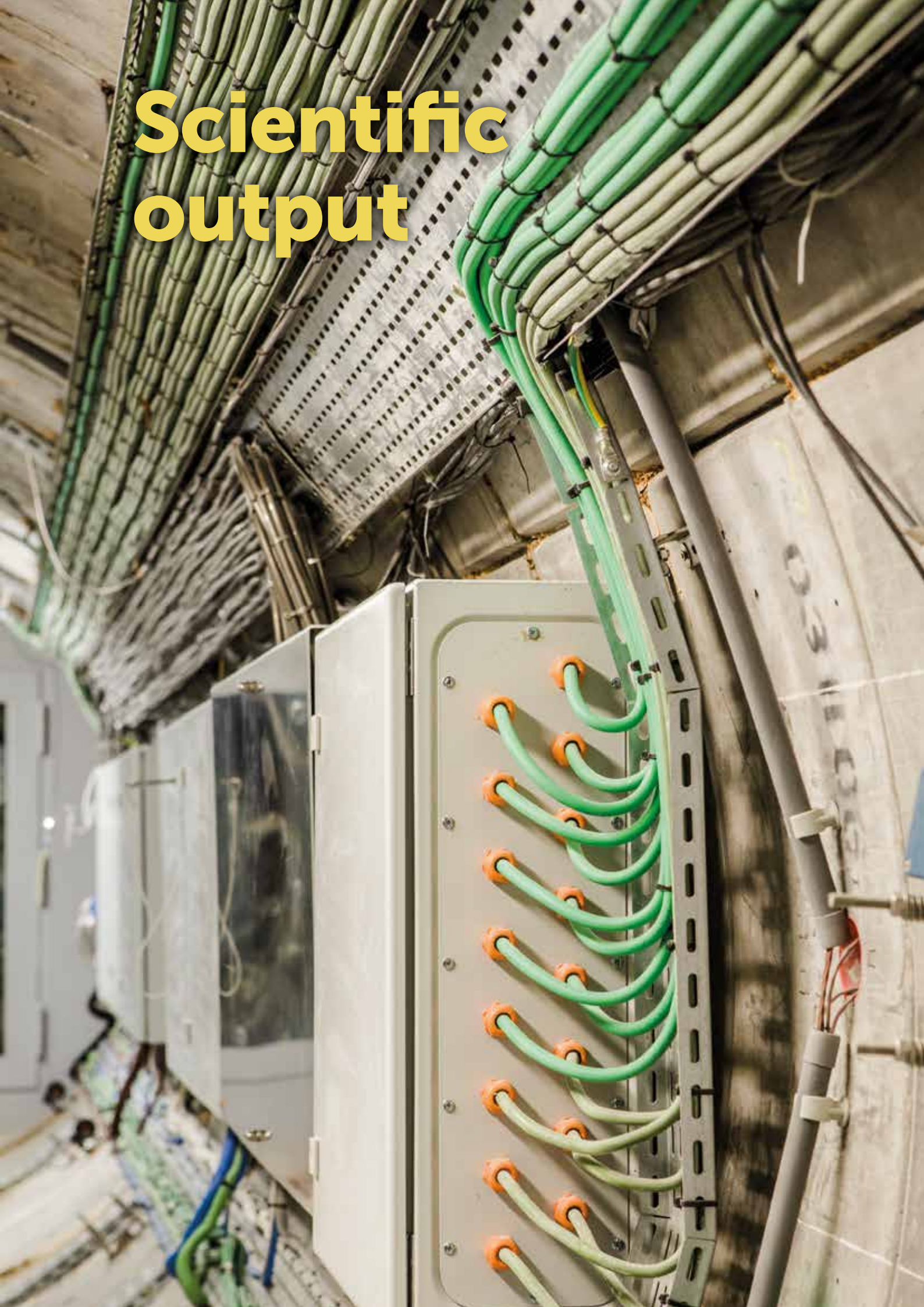
[4] https://parismatch.be/actualites/societe/573999/nucleaire-la-belgique-va-t-elle-enfouir-ses-dechets-les-plus-dangereux

## 6. Exhibitions

From 19 February to 25 April 2021, Belgian artist Cécile Massart held an exhibition called "Sarcophagi" at Botanique in Brussels. The exhibition addresses questions of knowledge and memory preservation and how to communicate with future generations. EURIDICE has provided objects that were exposed, such as a drill cores and a mould used in a mock-up experiment of a supercontainer.


Figure 31 – Artist Cécile Massart at the *"Sarcophagi"* exhibition

# Scientific output



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## List of abbreviations

| | |
|---|---|
| **ANDRA** | Agence Nationale pour la Gestion des Déchets Radioactifs (FR) |
| **CLIPEX** | CLay Instrumentation Programme for the EXtension of an underground research laboratory |
| **EBS** | Engineered barrier system |
| **EC** | European Commission |
| **EDZ** | Excavation-damaged zone |
| **EURAD** | European Joint Programme on Radioactive Waste Management and Disposal |
| **EURIDICE** | European Underground Research Infrastructure for the Disposal of nuclear waste in Clay Environment |
| **FANC** | Federal Agency for Nuclear Control (BE) |
| **FEM** | Finite Element Method |
| **GSIS** | GeoScientific Information System |
| **HADES** | High-Activity Disposal Experimental Site |
| **Modern2020** | Development and Demonstration of monitoring strategies and technologies for geological disposal (within the framework of the Horizon 2020 Euratom Work Programme) |
| **ONDRAF/NIRAS** | Belgian Agency for Radioactive Waste and Enriched Fissile Materials (BE) |
| **PRACLAY** | Preliminary Demonstration Test for Clay Disposal |
| **PUP** | Public-public partnership |
| **ROM** | Reduced Order Model |
| **SCK CEN** | Belgian Nuclear Research Centre (BE) |
| **THM** | Thermo-hydro-mechanical |
| **THMC** | Thermo-hydro-mechanical-chemical |
| **UPC** | Universitat Politècnica de Catalunya (ES) |
| **URL** | Underground research laboratory |
| **URF** | Underground research facility |
| **W&D** | Waste and Disposal, an SCK CEN expert group |

ESV EURIDICE EIG

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

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