2023 and 24

Activity Report

EURIDICE

Contents

General foreword

Marc Demarche, Chairman of the Board of EURIDICE

Dear reader,

EURIDICE is a general partnership between ONDRAF/NIRAS and SCK CEN, founded in 1995 and currently established until 2045. With the start of the public-public partnership (PPP) between SCK CEN and ONDRAF/NIRAS from January first 2021, a broader collaboration between both organisations started, which also had an impact in the operating framework of EURIDICE. Although the PPP does not change the statutory tasks, which were established by a notarial deed in April 2019, it creates a new framework of cooperation between the two members. 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 2023 and 2024.

In 2023 and 2024, there was a strong focus on the roll out of the PPP and strengthening of the bonds between the partners. This was also the case for EURIDICE, having a central role with its involvement in most of the domains. EURIDICE was also involved in EURAD-1, the first project within the European programme for radioactive waste management running from 2019 to 2024. The work packages HITEC, on the influence of temperature on clay-based material behaviour, and GAS on mechanistic understanding of gas transport in clay materials were very successful with contributions of EURIDICE. EURAD-2 was started in October 2024 and will again have involvement of EURIDICE in the OPTI work package on HLW repository optimisation including closure. These international collaborations give great opportunities to demonstrate our capabilities and expand our knowledge.

After the very busy previous years of refurbishment of the old access shaft to the HADES URL, which was completed in 2021, the operation and safety activities of HADES were more focused on the stability of the HADES galleries, the day-to-day management, and maintenance of the installation. It however became clear that a (partial or stepwise) refurbishment of the second shaft will also be necessary in the foreseeable future. The preparations for this renovation are currently ongoing.

For many years, the large-scale *in situ* 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 the summer of 2015. In 2023 and 2024 we successfully continued this large-scale test and completed 9 years of heating at 80°C in August 2024. We also took the time to celebrate 10 years of the start of the heating of PRACLAY with the team in November 2024. The heating phase will continue into 2025, when, after 10 years of heating at 80°C, a cooling and dismantling phase is planned. All components of this large-scale test are still operating as expected and the 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 large-scale *in situ* PRACLAY Heater Test resulted in several publications in reputable scientific journals in 2023 and 2024, a quick google scholar search will come up with no less than 9 PRACLAY related papers. Such publications form an important pillar of the scientific basis for geological disposal and of the knowledge management of EURIDICE. In this way, the results of the large-scale *in situ* PRACLAY Heater Test are peer reviewed and are part of the wider scientific domain contributing to the preservation of this knowledge and expertise.
In 2023 and 2024, there were plenty of visits to the HADES URL. Since the opening of the visitor centre Tabloo in Dessel, visits to HADES are limited to technical and/or scientific actors and those who play

an important role in the decision-making process for geological disposal, whereas before the COVID-19 pandemic, secondary schools and all socio-cultural groups were welcomed. The latter are now redirected to Tabloo, which has been very successful at attracting a large audience over the past years. The groups that now visit HADES are exclusively from universities, waste management organisations and research institutes, political stakeholders, etc. This also entails that the visits are exclusively guided by the EURIDICE personnel and contribute even more to our networking. Overall, we welcome on average 80 groups per year, totalling about 1000 individual visitors who descend to HADES. Moreover, the EURIDICE communication team organises PPP-related events such as the annual Exchange Meeting, a networking and scientific knowledge exchange event welcoming over 100 participants.

Lastly, I would like to sincerely thank Peter De Preter for sixteen years of dedicated service as Director of EURIDICE. Throughout his tenure, Peter played a pivotal role in guiding the team through significant milestones, including the successful start-up of the PRACLAY experiment and the extensive renovation of Shaft 1. Peter now dedicates his expertise and energy to other important projects within ONDRAF/NIRAS, ensuring his contributions to the field remain invaluable. He has passed the torch to Maarten Van Geet mid-2024, who was appointed Director ad interim of EURIDICE. With his extensive experience and deep understanding of the organization, Maarten is well-positioned to lead EURIDICE through this transitional period and beyond.

Marc Demarche, Chairman of the Board of EURIDICE

EURIDICE: history, tasks and fields of expertise

EURIDICE (European Underground Research Infrastructure for Disposal of nuclear waste In Clay Environment) is a general partnership between 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, EURIDICE contributes to the national disposal programme for high-level and long-lived waste managed by ONDRAF/NIRAS. EURIDICE also contributes to the surface disposal programme of ONDRAF/NIRAS for low-level waste, validating its know-how in the domain of monitoring. These activities are however not discussed in this report.

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 since 1995.

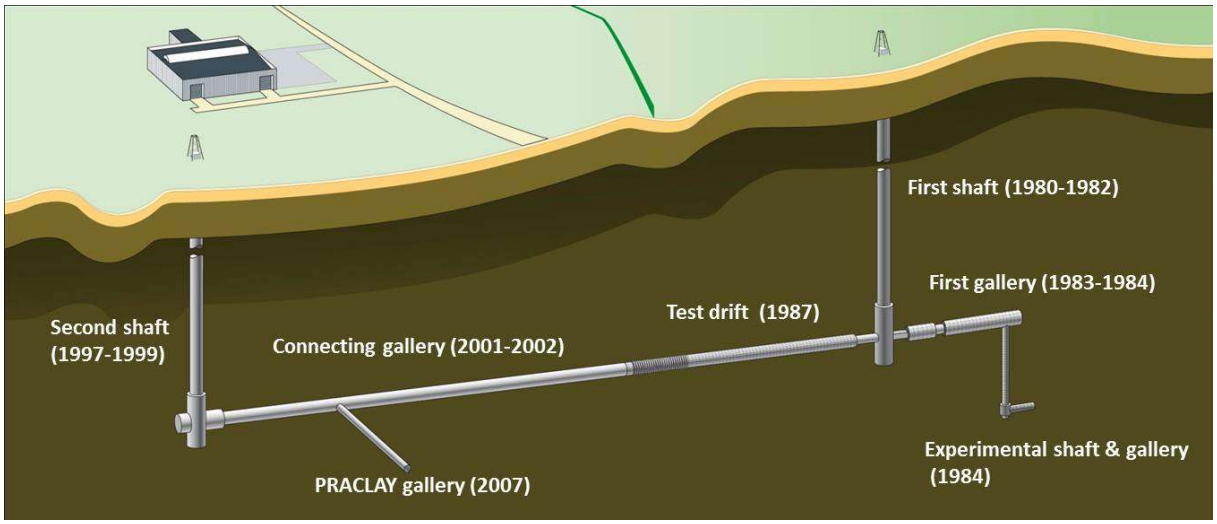


Figure 1 – The underground research laboratory HADES (High-Activity Disposal Experimental Site)

The main statutory tasks of 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 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 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 EURIDICE enters into partnerships or other agreements with third parties, in so far as this does not jeopardise the above statutory tasks.

After more than 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 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.

The excavation and construction techniques used by EURIDICE have 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 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. 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 the 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 projects in this area, with *in situ* experiments in the HADES URL, are the large-scale *in situ* PRACLAY Heater Test and the NEMESIS gas diffusion experiment. Within the PRACLAY Heater Test, 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 the NEMESIS experiment, the knowledge acquired at small laboratory scale on gas transport is tested at larger scale, currently with a focus on the gas diffusion properties.

Thirdly, instrumentation and modelling expertise is crucial to the work of the EURIDICE team. In the HADES URL, sensors have been operational and gathering data for a very long time already, some for more than 40 years. This long-term monitoring gives EURIDICE a unique insight in the stability of galleries, pore water chemistry, hydromechanical properties and evolution of the Boom Clay due to excavation, and many other important factors for the safety case of deep disposal. Indeed, intensive use of measuring instruments in the specific context of geological disposal research has helped EURIDICE gain considerable expertise in this field for decades. It also draws upon this expertise to support other tests such as the surface testing of the supercontainer and tests for the caissons of the category A surface disposal facility. The HADES underground research laboratory contains hundreds of measuring instruments. These are used during experiments or construction work to measure total pressure, pore water pressure in the clay, temperature in the clay, relative humidity, and movements and deformations of the clay or the gallery lining. Once they have been placed in the clay, the instruments are often inaccessible and can no longer be repaired if they fail. They also need to be waterproof and resistant to high pressure. Many sensors are therefore specially adapted or custom-made, making this the third key expertise of EURIDICE.

With its RD&D activities and fields of expertise, EURIDICE contributes to the national program for the disposal of high-level and long-lived waste managed by ONDRAF/NIRAS. With the royal decree published on October 28th 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 established geological disposal as a reference solution. ONDRAF/NIRAS has ordered the King Baudouin Foundation to organise a national debate which has been organised between March 2023 and 2024. Based on the outcome of this debate, the following steps in the decision-making process for the implementation of geological disposal are currently defined. The work of EURIDICE will continue to support and guide the needs of ONDRAF/NIRAS during these following steps.

EURIDICE today

1 Organisation

EURIDICE is governed by a four-person management board**,** called **'College of Directors of EURIDICE'** (Figure 2). ONDRAF/NIRAS and SCK CEN each appoint two board members for a period of three years. The Chairman of the College of Directors is appointed by ONDRAF/NIRAS. The Secretary of the Board, the Team Manager and the Director of EURIDICE attend meetings in an advisory capacity. The government commissioners of both members are invited to attend the meetings of the board.

Figure 2 –The college of directors

The college members in the period 2023-2024 were as follows:

- Marc Demarche, Chairman, Director-General of ONDRAF/NIRAS
- Philippe Lalieux, Director long-term management ONDRAF/NIRAS
- Peter Baeten, Director-General of SCK CEN
- Christophe Bruggeman, Deputy Director-General of SCK CEN

Responsibility for day-to-day management of EURIDICE lies with the **Director**, who is appointed by ONDRAF/NIRAS. The Director is assisted by the **Team Manager**, appointed by SCK CEN (Figure 3).

Figure 3 - Maarten Van Geet, director and Mieke De Craen, team manager of EURIDICE.

The College of Directors of EURIDICE is advised by three internal bodies (Figure 4): 1) the consultative committee on safety, health, environment & security, 2) the consultative committee on communications and 3) the consultative platform on RD&D. Since 2021, the latter consultative platform consists of the members of the PPP coordination committee. These bodies support 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 EURIDICE, and the Director and/or Team Manager of EURIDICE. The committees identify the objectives and priorities of EURIDICE in each of the three fields. They meet on a regular basis and report to the College of Directors of EURIDICE.

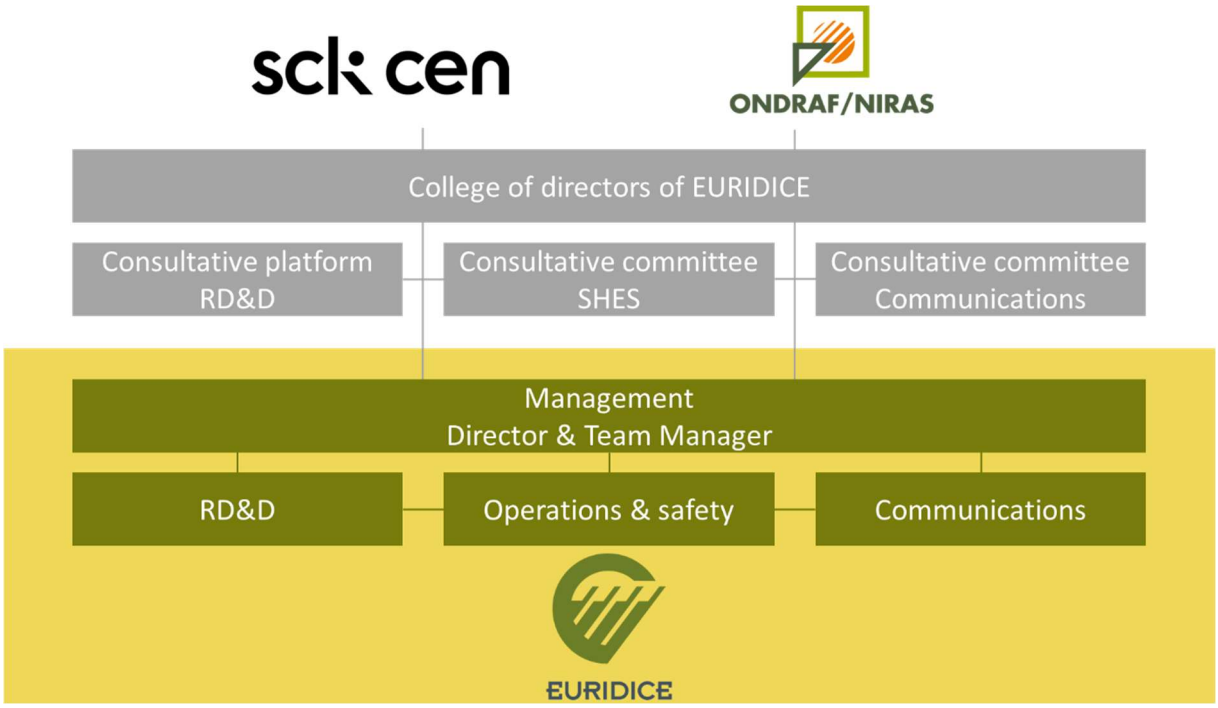


Figure 4 – Organization and governance of EURIDICE.

With the approval of the new **Statutory Rules** for EURIDICE in 2019, the lifetime 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 EURIDICE and in the HADES URL.

2 EURIDICE team

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

Figure 5 - The EURIDICE team

In 2023 and 2024, the EURIDICE team was composed of the following people:

Director: Peter De Preter (until 15 May 2024)

Director at interim: Maarten Van Geet (since 16 May 2024)

Team Manager: Mieke De Craen

Management Assistant & QA: Caroline Poortmans and Miguel Postigo Sanchez (since 19 August 2024)

RD&D process:
Arnaud Dizier – scientific collaborator
Temenuga Georgieva – scientific collaborator

Guillaume Flood-Page – scientific collaborator (since 18 March 2024)
Jan Verstricht – scientific collaborator
Dries Nackaerts – scientific collaborator

Operations and safety process:
Kevin Schuurmans – manager
Dries Nackaerts – technical collaborator
Jo Heylen – technical collaborator (since 1 January 2023)
Bram Olijslagers – technical collaborator
Bert Vreys – technical collaborator
Johan Peeters – technical collaborator (until 31 March 2023)

Communication process:
Katrien Hendrix – coordinator (since 1 October 2023)
Els van Musscher – administrative collaborator
Carine Slootmakers – practical assistance

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

In 2023 and 2024, 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. The coordination committee of the PPP provides consultation for the EURIDICE RD&D programme, ensuring it fits into the Belgian programme on radioactive waste management.

The RD&D programme includes the follow-up of the large-scale *in situ* PRACLAY Heater Test that has been running since 2014. Section 1 provides an overview of the main observations obtained from this Heater Test. After 10 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 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 2 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. The mapping of the concrete blocks in the test drift has also been under investigation recently. A large campaign has managed to generate an overview of the test drift stability and the clay-concrete interactions in this part of HADES, making the test drift our largest, long-running experiment. Lastly, the work on feasibility of a geological repository has been explored further in the past two years with an additional research line.

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 large-scale *in situ* PRACLAY Heater Test. In 2023 and 2024, PRACLAY remained very important in our RD&D programme. Furthermore, the focus shifted to continued monitoring of the gallery geometries and stability of the gallery linings. Moreover, environmental monitoring, instrumentation and monitoring of the ongoing experiments in HADES are prioritised. This is discussed in section 3.

Section 4 gives an overview of EURIDICE's international activities, mainly our contribution in several Work Packages of the European Joint Programme on Radioactive Waste Management and Disposal (EURAD-1).
Finally, section 5 gives an update of the four PhDs that EURIDICE supports.

1 The large-scale PRACLAY *in situ* 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, EURIDICE is making an important contribution to the Belgian 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** 6. 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.

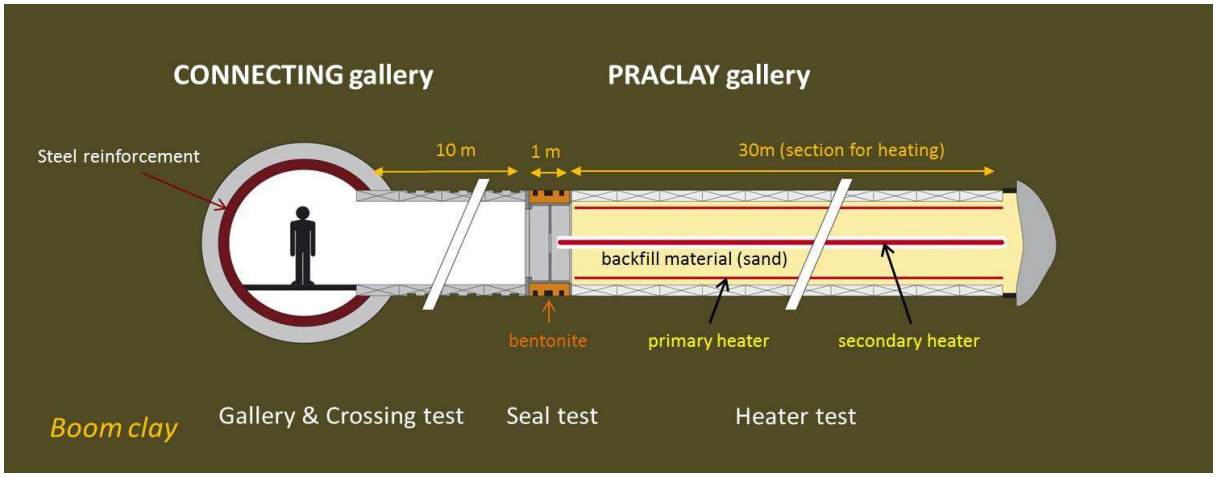


Figure 6 – Design of the PRACLAY gallery and experiments

The excavation of the Connecting gallery using a tunnelling machine demonstrated the feasibility of constructing galleries on an industrial scale (Bastiaens et al., 2003). 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 (Van Marcke et al., 2013). The large-scale PRACLAY *in situ* Heater Test, finally, focuses 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 Heater Test is discussed in the following sections.

For 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 large-scale *in situ* PRACLAY Heater Test was published in 2013, upon conclusion of the installation phase of the experiment (Van Marcke et al., 2013).
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. Two detailed reports on the experimental evolution during the start-up phase and during the first years of the stationary phase were published in 2016 and in 2017 (Dizier et al., 2016; Dizier et al., 2017).
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 a uniform temperature at this interface around the target temperature of 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 early predictions made by modelling (Chen et al., 2021).

1.1 Evaluation of the PRACLAY Heater test

By the end of 2024, the PRACLAY Heater test had been running for more than 9 years at a temperature close to 80°C at the clay-concrete lining interface. 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. Due to the heterogeneous temperature distribution along the Boom Clay/lining interface, as illustrated by the temperature profiles in Figure 7, two thermal indicators, Tind1 and Tind2, were defined. These indicators represent average temperatures for zones 2 and 3, respectively. This approach enabled better experimental control, ensuring the temperature could be maintained at 80°C during the stationary phase, as shown in Figure 8. These results demonstrate that the temperature at the interface between the gallery lining and the clay was successfully maintained at 80°C during the stationary phase of the test.

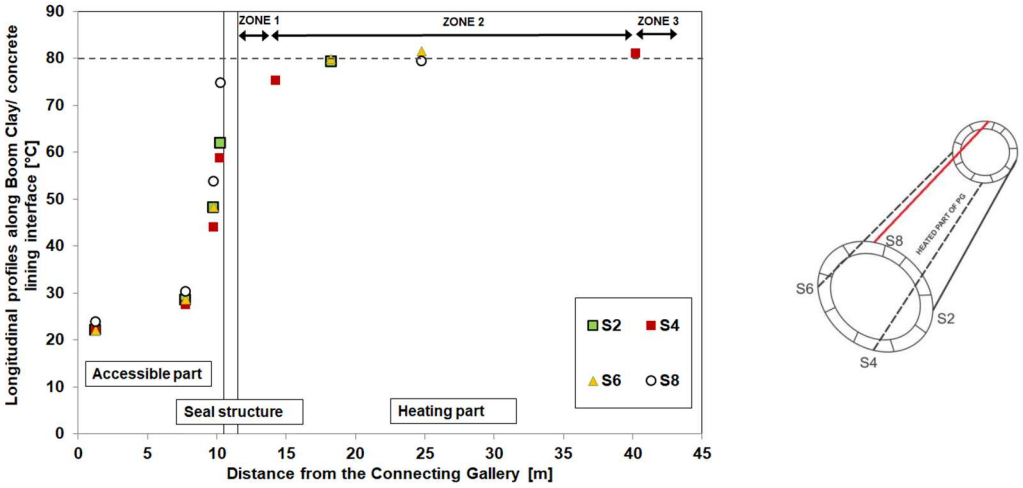


Figure 7 – Longitudinal profiles of the temperature along the extrados of the PRACLAY Gallery lining

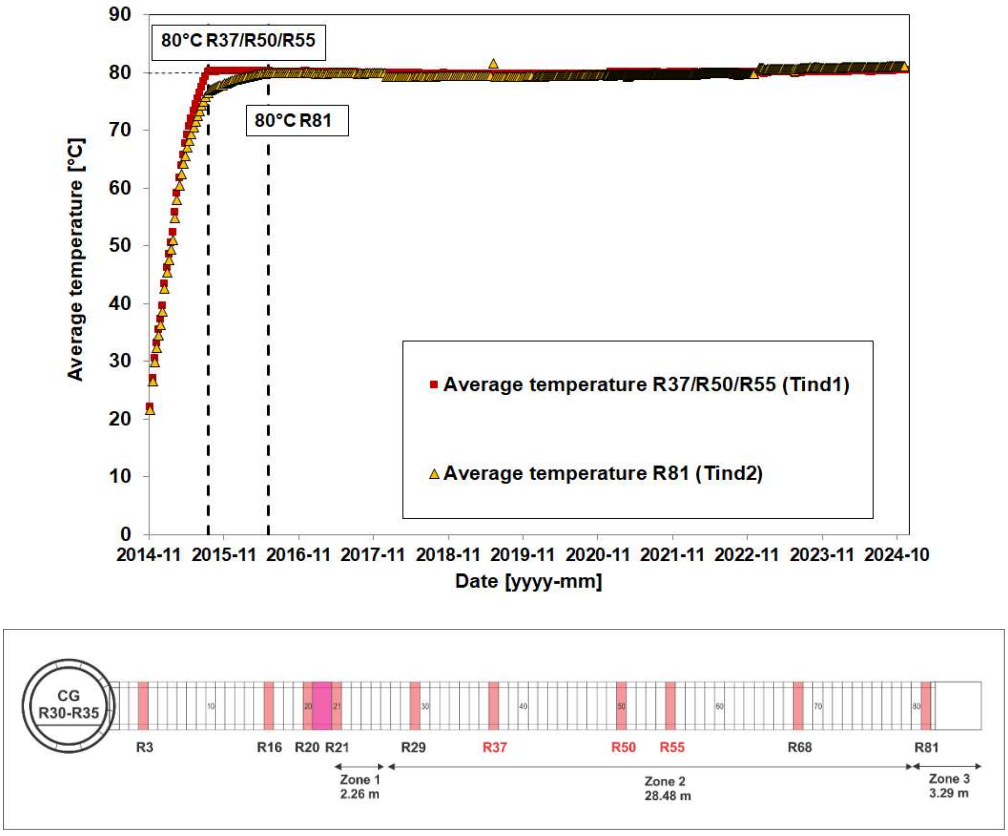


Figure 8 – Average temperature evolution measured using the extrados sensors in gallery rings R37, R50 and R55 (Tind1) and R81 (Tind2)

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 9. As can be seen, the pore water pressure

is maintained at a level of approximately 2.8 MPa. Even under quasi-undrained conditions, a small decrease in pore water pressure is observed due to the dissipation of pressure within the surrounding environment.

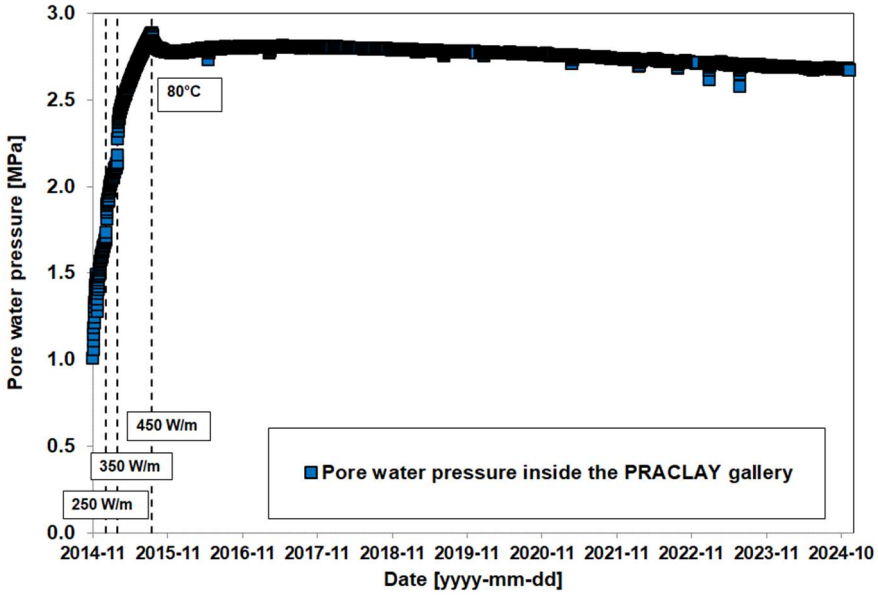


Figure 9 – Pore water pressure evolution inside the backfilled part of the PRACLAY gallery

So far, the segmental concrete lining has remained stable, ensuring secure 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 segments or embedded thermo-couples in the lining) or have delivered data with artefacts, thanks to the extensive network of instrumentation and the redundancy of critical sensors. The dedicated effort to analyse the long-term performance of all PRACLAY related sensors is described further (section 3.2).

The observations from more than 9 years of heating at 80°C 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.

1.2 Refining the characterisation of the Boom Clay

1.2.1 Viscoplastic modelling of Boom Clay

Previous attempts at modelling *in situ* experiments such as Atlas IV and PRACLAY have so far concentrated on the elastoplastic nature of Boom Clay, thereby disregarding the known time-dependent nature of the clay. Work is currently ongoing to quantify the importance of the viscous behaviour of Boom Clay when simulating its THM behaviour. To achieve this, the ACC-2 constitutive

model, a two-surface "*Adapted Cam Clay*" model (Hong et al., 2016), has been implemented in COMSOL Multiphysics. Verification and validation of the model is currently ongoing, while its application to simulating the PRACLAY heater test is expected in the next months.
As can be seen in Figure 10 (left), the main advantage of this model is that, for a given pre-consolidation pressure p_c, the yield surface, which bounds the stress states that can be reached without the initiation of plastic strains, is much smaller than for more traditional models such as the Modified Cam Clay model (MCC). In consequence, small amounts of irreversible strain are generated at lower stress levels, better reproducing experimental observations. Adopting the framework of bounding surface plasticity, this plastic strain is limited while the Yield surface is small and far from the outer "*Bounding surface*", but progressively increases as the Yield surface nears the bounding surface. Illustrated in Figure 10 (right) in the case of an isotropic loading curve, this behaviour allows for a smooth transition from an over-consolidated towards normally consolidated behaviour.

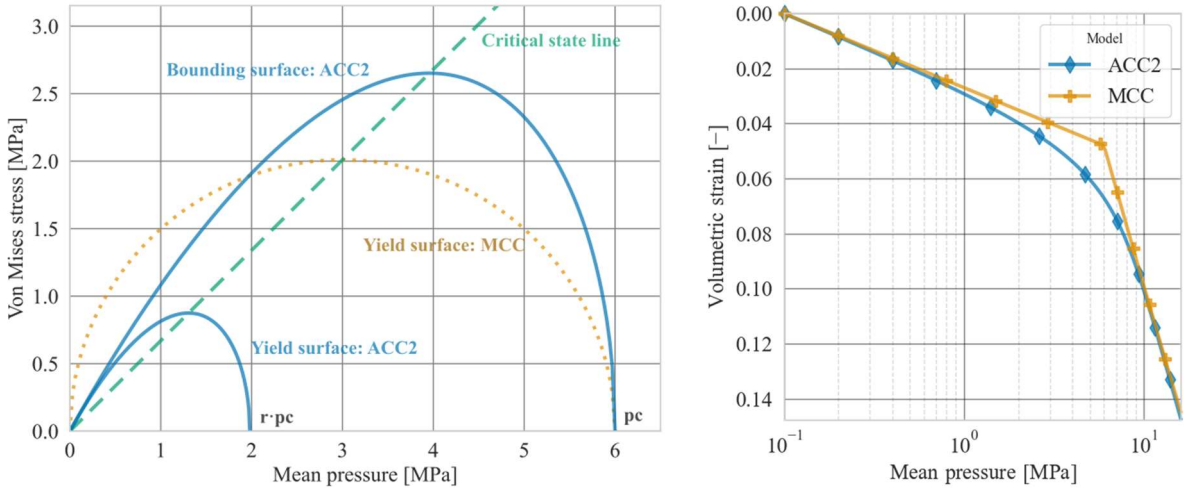


Figure 10 - Left: Yield surface of the Modified Cam Clay (MCC) model and both yield and bounding surfaces for the Adapted Modified Cam Clay (ACC-2) model Right: isotropic loading behaviour observed in COMSOL Multiphysics using both models.

Another advantage and the second reason for choosing this constitutive model is that an extension was developed to account for time-dependent behaviour, to better interpret the data. This was done during the PhD of May Awarkeh (Awarkeh, 2023). This extension will be integrated into the COMSOL constitutive model after verification and validation of ACC-2 are completed.

1.2.2 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 a unique opportunity to extract pore water from Boom Clay at in situ conditions. For over 40 years, pore water chemistry studies are carried out by SCK CEN's Waste and Disposal Group, with the support of EURIDICE. The pore water composition of the Boom Clay in Mol is hence

relatively well-known and well-understood. Several publications can be consulted on this topic, e.g. De Craen et al. (2004, 2008), Honty et al. (2022), Wang et al. (2023).

By sampling the pore waters around the PRACLAY gallery, the impact of elevated temperatures on the pore water composition is being examined. Four in-situ sampling campaigns were conducted between 2021 and 2024. During these campaigns, 31 pore water samples were obtained from the piezometer filters placed around the PRACLAY Heater test and exposed to variable temperatures between 36 and 69°C (Figure 11). The pore water samples have been analysed for their pore water and gas composition and microbial characteristics. In addition, geochemical modelling is being done to better understand the geochemical processes involved. As this study is still ongoing, reporting on the impact of elevated temperatures on the Boom Clay pore water composition around the PRACLAY Heater test is foreseen in the next year.

Figure 11 - Cabinets for simultaneous sampling of pore water, dissolved gasses and analyses of geochemical parameters at in-situ conditions, to study pore water geochemistry around the PRACLAY gallery.

1.3 Preparation of the cooling phase

The stationary phase of the PRACLAY Heater test was planned to last 10 years from August 2015 to August 2025. This means that the heating phase would end next August after which the cooling phase could start. Only after the PRACLAY gallery has cooled down sufficiently can the experimental setup be dismantled.

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.

To prepare for this cooling phase, four scenarios are being investigated based on the level of heater power reduction applied at the end of the heating phase: 10%, 20%, 50%, or 100%. Figure 12 and Figure 13 present these four scenarios in terms of heater power variation and the resulting evolution of temperature and pore water pressure, respectively. In the case of a complete switch-off (100% reduction), it can be observed that the temperature drops rapidly at the beginning of the cooling phase before gradually decreasing more slowly. It will take more than two years before to have a temperature lower than 30°C at the clay-lining interface. The pore water pressure (Figure 13b) presents an abrupt decrease at the beginning before a quasi-stabilized phase. This means that the pore water pressure will need to be manually drained by extracting a certain amount of water before achieving good conditions for dismantling.

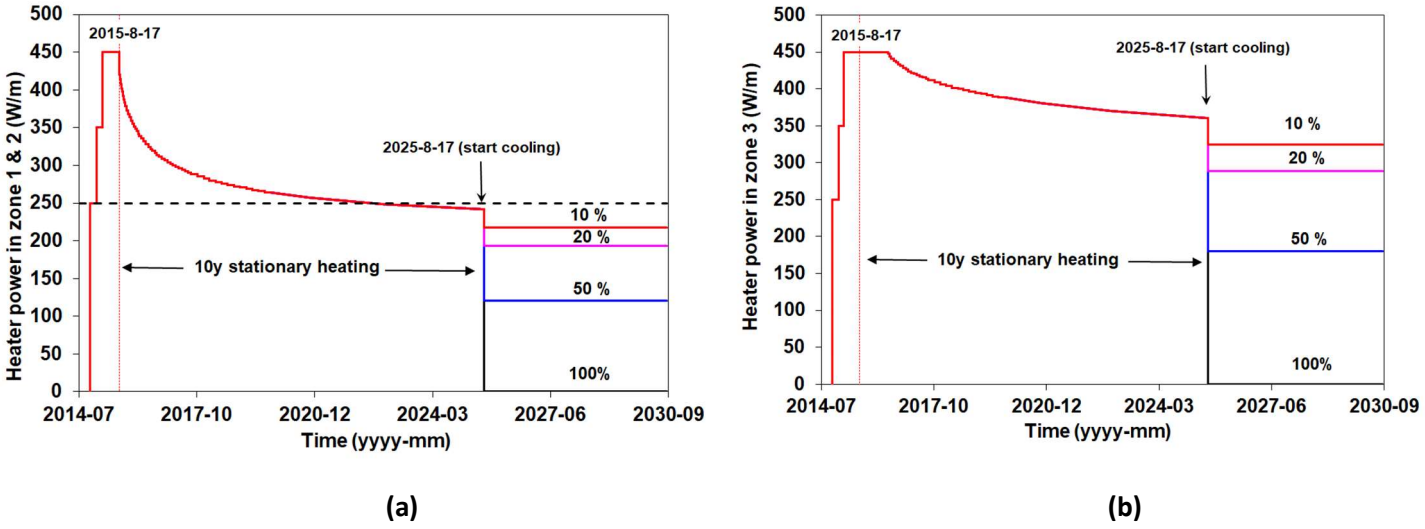


Figure 12 - Evolution of the heater power considering the four scenarii (10%, 20%, 50% and 100% of reduction) in zone 1 &2 (a) and in zone 3 (b)

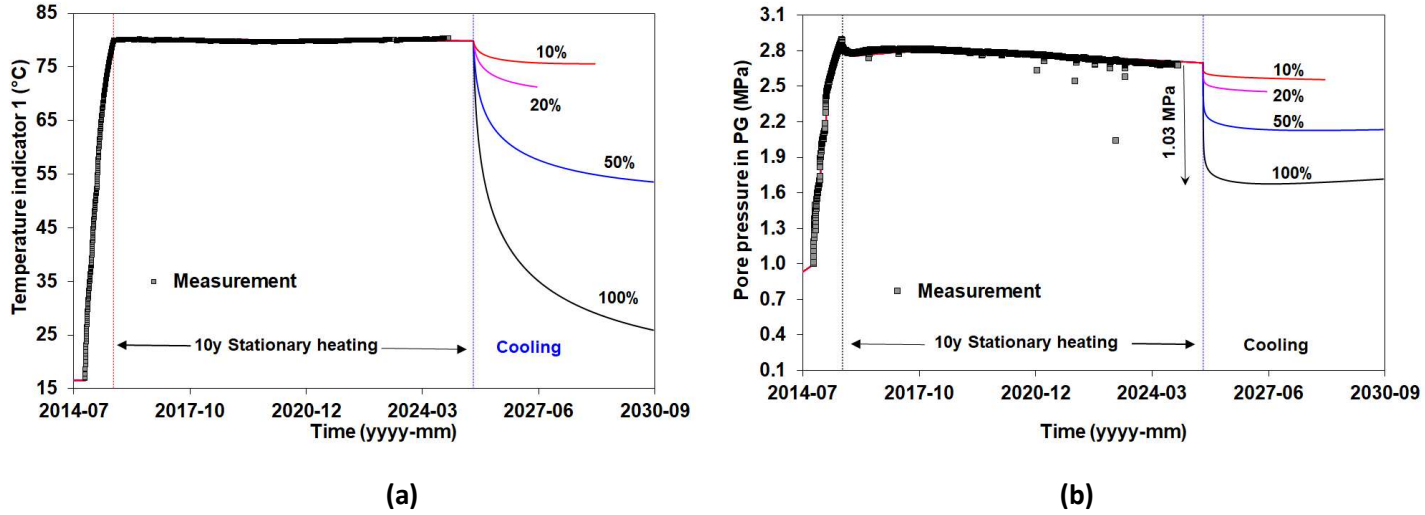


Figure 13 - Evolution of the temperature (a) and of the pore water pressure (b) considering the four scenarii (10%, 20%, 50% and 100% of reduction)

2 Repository feasibility studies

The Belgian Research, Development, and Demonstration (RD&D) programme on the geological disposal of high-level and/or long-lived radioactive waste aims to demonstrate the feasibility of the construction, operation, and closure of the concept for geological disposal of radioactive waste in clay. In this context, the HADES URL plays an important role in the demonstration of the technical feasibility of constructing galleries in a poorly indurated clay. Major achievements were the construction of the Test Drift gallery in 1987 and the Connecting Gallery in 2002, which have been monitored since their construction.

Within this context, the recent contribution of EURIDICE covers:

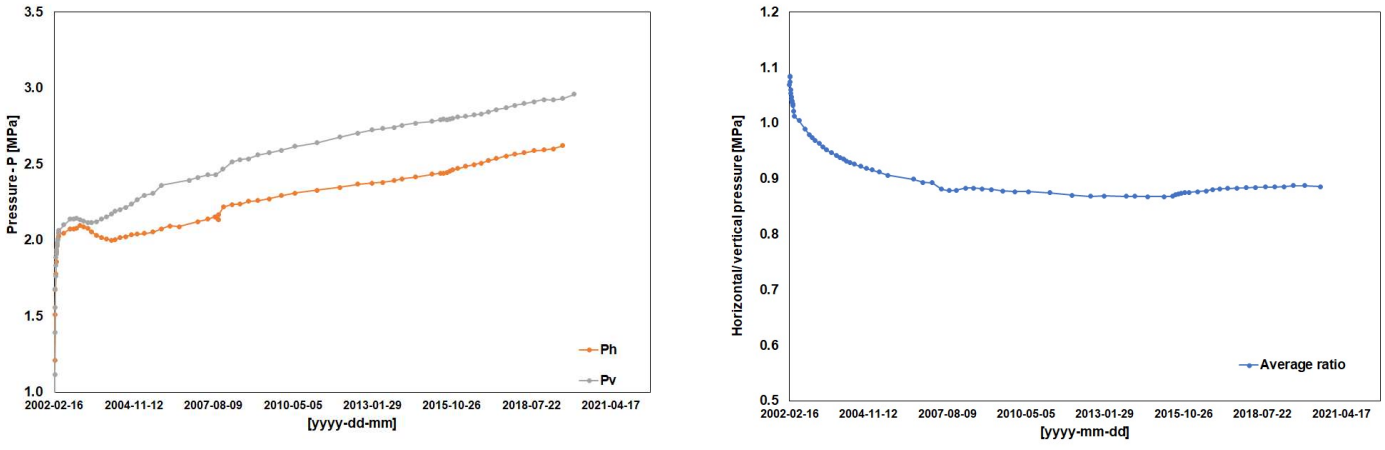
- Monitoring and analyses of the long-term behaviour of the galleries at HADES URL.

- Lessons learnt on the stability analysis of the galleries at HADES URL for the repository design.
- Thermo-hydro-mechanical analysis of a geological disposal facility for high-level radioactive waste in clay formations.

Recently, a framework document has been proposed, which provides a systematic and consistent approach for designing a geological disposal facility (GDF) at 200 m depth in poorly indurated clay (Rubio and Dizier, 2024). The overarching design objectives, principles, and requirements that must guide all design activities are described in this document. Specifications on the physical properties of the host rock to be considered are also provided, as well as the operational loads that the repository will encounter during disposal and closure phases. It also defines the design criteria, translating performance objectives into measurable physical property values. Additionally, a systematic design methodology for the repository's architectural elements is presented, along with modelling and documentation requirements to ensure quality and compliance. This framework document will be further elaborated in order to support the design of the future repository.

2.1 Stability analysis of the HADES galleries

To study the stability of the Connecting gallery, an inspection plan was defined, consisting of the follow-up of the convergencies, the embedded vibrating strain gages and the monitoring of the misalignment between segments. The stresses inside the segments can be assessed based on the strain evolution and the external pressure acting on the lining can be back-calculated with the stresses. Figure 14 presents the evolution of the external pressure (in (a)) and the evolution of the ratio between the horizontal and the vertical pressure (in (b)). It can be observed that the external pressure increased quickly at the beginning when the contact between the clay and the lining was established before to progressively increase more slowly. 20 years after the construction of the gallery, the vertical pressure reached a value around 3 MPa corresponding to 67 % of the total *in situ* vertical pressure undisturbed (4.5 MPa). The evolution of the ratio (Figure 14) shows that the value remains inferior to 1 meaning that the vertical pressure is higher than the horizontal.



(a) (b)

Figure 14 – (a) Evolution of the vertical and horizontal external pressure acting on the lining, average value over the three instrumented rings. (b) Evolution of the ratio between the horizontal and the vertical pressure, average value over the three instrumented rings.

All measurements conducted within the Connecting Gallery in 2024 have been summarized in a dedicated report (Dizier and Georgieva, 2024). The report concludes that the gallery's evolution is proceeding as expected, with no indications of abnormal developments or sudden changes in monitored parameter.

In 2023 and 2024, the stability analyses were extended to the Test Drift (Georgieva and Dizier, 2024). The Test Drift was excavated in 1987. The 40 m long gallery was lined with a 60 cm thick concrete segmental lining composed of 64 concrete blocks and intercalary wooden plates in between the segments in a ring (Neerdael et al., 1992). Since its construction, numerous experiments have been launched and many of them are still ongoing (Li et al., 2023). It is therefore important to ensure a stable and safe environment for these experiments but also for the general safe operation of the underground laboratory.
After about 37 years of exploitation (the Test Drift was excavated in 1987), some deteriorations at the surface of the intrados of the concrete segmental lining are observed in the form of cracks or spalling. Therefore, an important aspect of the long-term stability of the gallery is the assessment of the current state of the Test Drift lining. In this context, a preliminary stability study was launched in 2023 with the main objective of assessing the current condition of the Test Drift and proposing an elaborate inspection and monitoring programme that would allow to follow the evolution of the gallery over time. The study was divided in several parts.

In the first part, the available construction archives were exploited to understand the building of this structure, i.e. the excavation technique and the placement of the lining segments.

In the second part, a monitoring plan was developed for mapping the damages observed on the surface of the lining segments. To this end, several types of damages were identified and were carefully documented. In addition, a detailed photo documentation of the gallery lining was carried out. This provides sufficient information to determine and analyse the distribution of these damages and to identify several zones where particular attention needs to be paid. Three zones of more pronounced deterioration were identified, namely between rings 5 to 34, 57 to 76 and 122 to 126 (Figure 15). The existence of the first two zones is suggested to be due to a combination of factors linked to the excavation technique, such as the learning phase (especially at the beginning) and the use of a semi-manual excavation technique. The last area, between the ANDRA gallery and the Connecting Gallery, is more complex because of the possible interaction between the Test Drift and ANDRA Gallery.

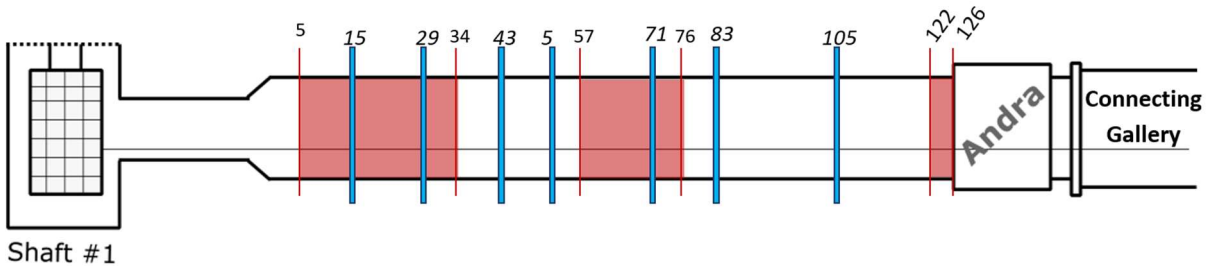


Figure 15 - Non-scale representation of part of HADES URL (Fist Shaft, access gallery, conical transition, Test Drift, ANDRA gallery and Connecting Gallery), showing the zones of increased damages (red colour) and the instrumented rings.

In a third step, the convergence measurements in the gallery are summarised and used to analyse the global response of the gallery lining when subjected to the evolution of the external clay pressure. It is seen that the convergence rate reduces with time. Nevertheless, even after 37 years, the convergences

still occur, and the gallery has not reached a steady state. This underlines the time-dependent clay-lining behaviour. An attempt to correlate the convergence experienced by the instrumented rings with the observed damages on lining was also made. Using this data, it was possible to relate the higher convergences to the locations where more damages occur. In addition, the existence of preferential damage axes was determined just above the mid-height of the ring.

In the fourth step, numerical modelling was performed to understand the mechanisms causing the concrete deterioration. 2D and 3D finite element modelling were performed with the finite element software COMSOL Multiphysics ©. The 2D finite element modelling corresponds to the analysis of a ring in plane strain conditions. Different loading conditions and geometrical cases were modelled to try to reproduce the misalignment or the reduction of the thickness of the lining. The overall results indicate that for the considered *in situ* loading conditions and with the assumptions taken into account in this modelling, even a reduction of the lining thickness with 20 to 30 cm would still not exceed the ultimate strength of the concrete from the lining. Finally, the 3D model considers a segment of the lining with and without the presence of the central hole used to handle the segment during the construction of the gallery. It was found that the effect of the central hole in the segments would cause a significant increase in the stresses around the hole and could act as a weak point in the segments at the origin of damage initiation. This suggest that the holes of the segments are a point of attention when assessing the integrity of the lining and the global stability of the gallery.

The combination of the on-site work together with the results from the numerical modelling indicate that the cause of the damages could be explained by a combination of factors and more particularly pinching effect between blocks and presence of the hole in a segment. However, this preliminary study revealed that these processes were only superficial and that no overall stability issues were identified. Nevertheless, the progression of deterioration must be closely monitored to prevent potential instability issues that could compromise the safe operation of the gallery. To achieve this, the characteristic time of damage progression must be assessed, and various techniques are currently being investigated to determine this timeframe. This will provide valuable input for the design and management of underground galleries in a deep geological repository.

A workshop was organized in February 2024 with an objective to present the main results of the preliminary study and to define the following actions. As a result, short-, mid-, and long-term actions have been defined to ensure the follow-up of the gallery. These actions have been integrated in an elaborated monitoring programme of the gallery, which aims to ensure that the current condition and the evolution of the gallery are well captured and understood. The long-term monitory of the gallery contributes to the stability study of the galleries at HADES URL and to the safe exploitation of the laboratory.

2.2 Feasibility studies

In 2023 and 2024, a close collaboration was established between EURIDICE and ONDRAF/NIRAS to address questions related to the design of a feasible geological disposal facility for category B&C waste at a depth of 200 metres in poorly indurated clay.

During 2023, ONDRAF/NIRAS requested EURIDICE to perform a technical review of all design documentation produced between 2018 and 2022 for costing purposes. Additionally, in the same year, ONDRAF/NIRAS, assisted by EURIDICE, visited several tunnelling technology manufacturers to investigate the constructability of the current reference solution.
As a result of these activities, ONDRAF/NIRAS concluded that, before proceeding further, several technical aspects of the current reference solutions and some of the assumptions made during the

earlier phase needed to be re-evaluated to confirm the technical feasibility and constructability of the reference solution. To address this, ONDRAF/NIRAS developed a systematic approach to design, focusing on calculating the individual architectural elements that will constitute the repository. To leverage 40 years of experience in the construction and operation of galleries in the HADES laboratory, ONDRAF/NIRAS decided to carry out this exercise initially at a hypothetical depth of 200 metres.
The objectives of this project are multiple and include:

1. **Supporting and advising ONDRAF/NIRAS** on all work commissioned for the design of a Deep Geological Repository (DGR).
2. **Conducting technical reviews and approvals** of all design work delivered on behalf of ONDRAF/NIRAS.
3. **Assisting ONDRAF/NIRAS** in developing a feasible geological disposal facility (GDF) at 200 metres in poorly indurated clay by:
    a. Supporting the development of the design framework document (prepared by ONDRAF/NIRAS).
    b. Designing architectural elements of the repository (specific elements to be determined at a later stage).
    c. Reviewing and approving design work carried out by contractors (when requested);
    d. Supporting the definition and assembly of the final repository (in collaboration with ONDRAF/NIRAS).

In 2024, EURIDICE contributed to the development of the design framework document, proposing a systematic method for designing a deep geological repository (DGR) and its components, such as access and disposal galleries, the intersections between two galleries, and the landing zone. In addition to this document, EURIDICE initiated the design of a component corresponding to the maximum gallery diameter that can be constructed in poorly indurated clay. This study was conducted using the finite element software PLAXIS, which is specialised in geotechnical analyses. The study is still ongoing but has already highlighted the challenges in accurately modelling the long-term behaviour of the clay and the interaction between the soil and the structure over time. The analysis indicates that certain simplifications are necessary. However, these simplifications must be further confirmed and validated to ensure their reliability.

3 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 to manage all the installed instrumentation.
The activities in this theme mainly consist of managing the installed instrumentation in HADES. It involves planning and following up on manual measurements, managing automated measurements, trouble shooting, etc. A second part of this theme is developing and implementing new projects for the improvement of the overall monitoring activities.

3.1 Routine monitoring tasks

While most monitoring in HADES has been automated, many monitoring tasks still require manual interventions. These tasks involve both monitoring performed by own personnel as well as

measurements by third parties (e.g. survey of HADES structure and components). A calendar is maintained to plan and coordinate all monitoring tasks in HADES. Most of these tasks are performed periodically, such as the read-out of the embedded strain gages in the Connecting Gallery in support of the THM studies, or the follow up of the displacement of the PRACLAY gallery done with a total station.
The (about 300) pressure transmitters in HADES are now calibrated every two years. As this is a rather labour-intensive and time-consuming process, a project has been started to automate this process. It consists in running the pressure calibrator automatically through a script. This work also includes reading the transmitter data and processing it through a calibration formula.
Investments into monitoring equipment (apart from regular maintenance) included a new pressure calibrator, a new total station for the follow-up of the displacement of the PRACLAY Gallery, and datalogging equipment to replace aging data-acquisition parts, some of which were installed more than 20 years ago.

3.2 Environmental monitoring

Following up the ventilation and environmental conditions in HADES are important both for scientific (e.g. boundary conditions of the experimental set-ups) and technical (e.g. efficiency and performance of the ventilation system) reasons.
The existing setup was installed after completion of the Connecting Gallery, and hence is more than 20 years old. Replacement and upgrading of the outdated setup were decided. In 2023 a temporary setup was installed to characterise in more detail the temperature and humidity variations and gradients in HADES. In 2024 this setup was extended with additional measuring points at the surface entrance of the second shaft. In 2025 the results of this new setup will be reviewed to reach a final sensor lay-out, including an upgraded sensing of air velocity and atmospheric pressure.

3.3 LabTool

In the context of a major overhaul of the data management, a gradual migration from the existing tools (database and local applications) to a uniform data management system is being performed, in which both the sensor data and the contextual information (metadata) are integrated. The data in the existing “Daily” database application was exported to the new LabTool environment In 2023. Due to the size of this dataset, it took a long time to organise and implement this data in LabTool. In 2024, intensive interactions with the database manager allowed to work out the strategy to organise LabTool in an efficient manner, and to ensure it is functional by the end of 2024.

4 International activities

International collaborations are crucial to the progress of national programmes, driving the advancement of shared knowledge on safe nuclear waste disposal. As an important actor in the Belgian programme for radioactive waste management, EURIDICE very much contributes to these initiatives. Through its participation in various international activities, including projects of the International Atomic Energy Agency (IAEA), the NEA Clay Club, and the European Joint Program on Radioactive Waste Management and Disposal (EURAD), EURIDICE contributes to preserving the scientific knowledge accumulated over the past 44 years. These collaborations also enhance the international visibility of the RD&D conducted at the HADES URL, facilitate the exchange of information and experiences with other geological disposal programmes, and provide opportunities to learn from practices abroad.

4.1 EURAD-1: European Joint Programme on Radioactive Waste Management and Disposal

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): *WP **MODATS** - Monitoring Equipment and Data Treatment for Safe Repository Operation and Staged Closure*, *and WP **MAGIC** - Chemo-Mechanical AGIng of Cementitious materials under coupled disturbances based on a multiscale approach*. These two projects were started in 2021.

EURAD-1 finished in 2024 but was continued into EURAD-2, which kicked off in October 2024, with EURIDICE contributing as linked third party from ONDRAF/NIRAS to work package ***OPTI*** - *HLW Repository optimisation including closure* (a strategic study).

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

For the disposal of heat-emitting high-level radioactive waste, it is important to understand the consequences of the produced heat on the properties (and their long-term performance) of the natural and engineered clay barriers. Most safety cases for disposal concepts involving clay currently consider a temperature limit of 100°C. Being able to tolerate higher temperature, whilst still ensuring appropriate performance, would have significant advantages (e.g. shorter above-ground cooling times, more efficient packaging, fewer disposal containers, fewer transport operations, smaller facility footprints, etc.). This Work Package (WP) aimed to enhance the understanding of how clay-based materials (host rock and buffer) respond to elevated temperatures (>100°C) over long durations in geological disposal systems for high heat-generating wastes (HHGW). It evaluated whether temperature limits between 100°C and 150°C are safe and feasible, investigating potential damage to the host clay/claystone formation (e.g., over-pressurization) and its consequences in the near and far field. The WP also studied the effect of temperature on bentonite buffer properties, such as swelling pressure, hydraulic conductivity, erosion, and transport, to ensure they continue to fulfil their safety functions.

In a first step of the WP (Task 1.2), a state of the art on the thermo-hydro-mechanical behaviour of the clay host geological formation was written in 2019 and published in 2020 (Villar et al., 2020) helping define a baseline concerning the knowledge about the three clay/claystone (Boom Clay, Callovo-Oxfordian Claystone and Opalinus Claystone) geological host formation and the engineered clay barrier. A comparison between these three clay(stone)s revealed their similarities and differences. Despite the differences in mineralogy and geological burial history, these geological formations all exhibit similar phenomena with a different time scale depending on their induration level. Later, with the progress realised within this WP, an updated version of the state of the art was redacted in 2024 highlighting the new experimental results and the conclusions of the benchmark exercises. This updated report, published as Deliverable 7.2 ("Updated state of the art on THM behaviour of I) buffer clay materials and II) host clay formations"(Villar et al., 2024)), is being considered for publication in

Frontiers in Nuclear Engineering (Radioactive Waste Management section) and is currently under review.

In a second task (Task 2.3), a series of benchmark exercises were proposed and modelled. The first modelling involved a generic case for three host clay/claystone formations: Boom Clay, Opalinus Claystone, and Callovo-Oxfordian Claystone, and was completed in early 2022 with a good agreement between all the modelling teams. The second step focused on modelling *in situ* heater tests at the underground research laboratories in Bure (France), Mol (Belgium), and Mont Terri (Switzerland). The modelling of the large scale PRACLAY Heater test was a collaboration between EURIDICE/SCK CEN, UPC (Barcelona), ULiège (Belgium), and BGE (Germany). The modelling of the large scale PRACLAY Heater showed that more advanced models are needed to reproduce the evolution of the pore water pressure around the gallery. These models include many different ingredients such as the anisotropy of the mechanical strength; the small-strain stiffness elastic behaviour, the variation of the permeability with the deformation or an artificial EDZ around the gallery with reduced parameters/ properties. The results were documented in Deliverable D7.6 written end of 2023 (de Lesquen et al., 2024). Additionally, at BGE's initiative, an article on the first benchmark exercise was written and accepted for publication in *Acta Geotechnica*, with its release scheduled for 2025.

4.1.2 WP GAS – Mechanistic understanding of gas transport in clay materials

The generation of gas in a geological repository is inevitable due to the anaerobic corrosion of metals present in the waste, the packaging and the galleries of the repository. Current research indicates that the gasses initially dissolve in the pore water and then are transported via diffusion and advection (Marschall et al., 2005). If the rate of gas production surpasses the host formation capacity to evacuate the gas by diffusion of dissolved gas, a free gas phase may form. This could lead to increased gas pressure, potentially impacting the integrity of the natural barrier (Levasseur et al., 2023; Jacobs et al., 2023). Therefore, a good understanding on the gas transport in low-permeability media like the Boom Clay is of primary importance for the Belgian RD&D Programme.

Until now, small-scale laboratory experiments (on samples of a few centimetres) have allowed the gas diffusion coefficient of Boom Clay to be defined under well controlled conditions (Jacobs et al., 2013). To validate this coefficient of dissolved gases of the Boom Clay on a larger scale, the NEMESIS (Neon diffusion in MEGAS *In situ*) *in situ* gas experiment was developed by SCK CEN, EURIDICE and ONDRAF/NIRAS within the Belgian Programme for deep geological disposal. Preparations for NEMESIS started in 2020 and it was added to the EURAD project, GAS Work Package later on, since it is within the scope of this project. The experiment was officially started on 5th September 2023 and is carried out in a collaboration between the 3 organizations.

The primary objective of NEMESIS is to confirm at a large scale (metres) the current knowledge about the diffusion coefficient of the Boom Clay and refine the understanding of gas transport processes under *in situ* conditions. Additionally, the experiment will bring new insights into the anisotropic gas transport properties of the Boom Clay.

The experiment is hosted in the Test Drift gallery, re-using boreholes of the MEGAS experiment drilled in 1992 (Volckaert et al., 1995; Ortiz et al., 2002). Four piezometers of the MEGAS setup arranged in a 3D layout are used. On one side, Neon gas is dissolved in water in a vessel connected to an introduction filter (source); on the other, Helium gas is dissolved in water in 3 vessels connected to 3 receiving filters. By monitoring the gas concentration evolutions over time in all three detection vessels, one can deduce the diffusion coefficient of dissolved Neon.

In September 2024, the NEMESIS experiment celebrated its first year. So far, no gas has been detected by receiving filters. According to the modelling predictions (Jacops et al., 2023), 2.5 to 3 years will be necessary for gas to diffuse from the introduction to the receiving filters. Nevertheless, a prior analysis of diffusion process is already possible by analysing the pressure decrease in vessels as a result of gas diffusion in the surrounding clay layers of the filters. During the period, the first estimates of the diffusion coefficients are in good agreement with the values measured in the lab, validating the good understanding of the diffusion process. However, this very promising result still need to be validated by continuing the experiment over the following years. The NEMESIS experiment is planned to last at least 5 years.
These first results have been recently presented at the 2024 Clay Conference in Hannover and been appreciated by the expert community as an important input for the upscaling of this gas transport process.

4.1.3 WP MODATS – Monitoring equipment and data treatment for safe repository operation and staged closure

The role of monitoring in geological disposal is acknowledged since many years and has been the subject of international collaborative work undertaken under the auspices of the IAEA, NEA and the EC. This work included consideration of monitoring strategies and the role of monitoring in decision making, R&D on sensor technologies suited to repository monitoring, and the role of monitoring when engaging with citizen stakeholders. Much of this work has been of strategic nature, and there was a need for significant R&D into specific fields such as data management, application of data to enhance system understanding, optimisation of monitoring systems and relevance of repository monitoring in societal dialogue.
The data provided by repository monitoring will be used in the iterative development of the safety case to support decision making during the different phases of repository implementation, from design to closure. Confidence in the data provided by the monitoring programme is an essential condition for this. The MODATS Work Package was established to address the issue of confidence in monitoring data. The ambition of MODATS was to consolidate the implementation strategy for monitoring systems by developing methods through which confidence can be demonstrated in the data acquired and benefits derived for repository implementation. Repository monitoring also presents challenges related to evaluation of multi-modal data, i.e. data that is measured by different sensors, resulting in a range of independent parameters, at different locations and at varying spatial and temporal sampling. R&D has therefore undertaken at two domains: (1) management of monitoring data (data acquisition, data processing – including validation – and presentation, and use of data in system understanding; and (2) sensor technology, by applying and adapting emerging technologies to waste repository monitoring, and developing new technologies that are suitable for the specific requirements of repository monitoring. Additionally, MODATS also looked at how interactions with citizen stakeholders on repository monitoring.

The MODATS WP lasted for 3 years, starting in June 2021 and ending in May 2024. In this WP, EURIDICE focused on the task on data management and continued the tasks that had started in 2021:

- 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.

The main activity in 2023 and 2024 was related to the management of experimental (monitoring) data. Together with the other organisations (ANDRA, NAGRA, Posiva and SKB), we used real experimental

data (in our case from PRACLAY) to develop and demonstrate methods to validate those data, including labelling, cleaning, and visualizing data. A generic workflow how to handle the data from acquisition to decision support is shown in Figure 16.

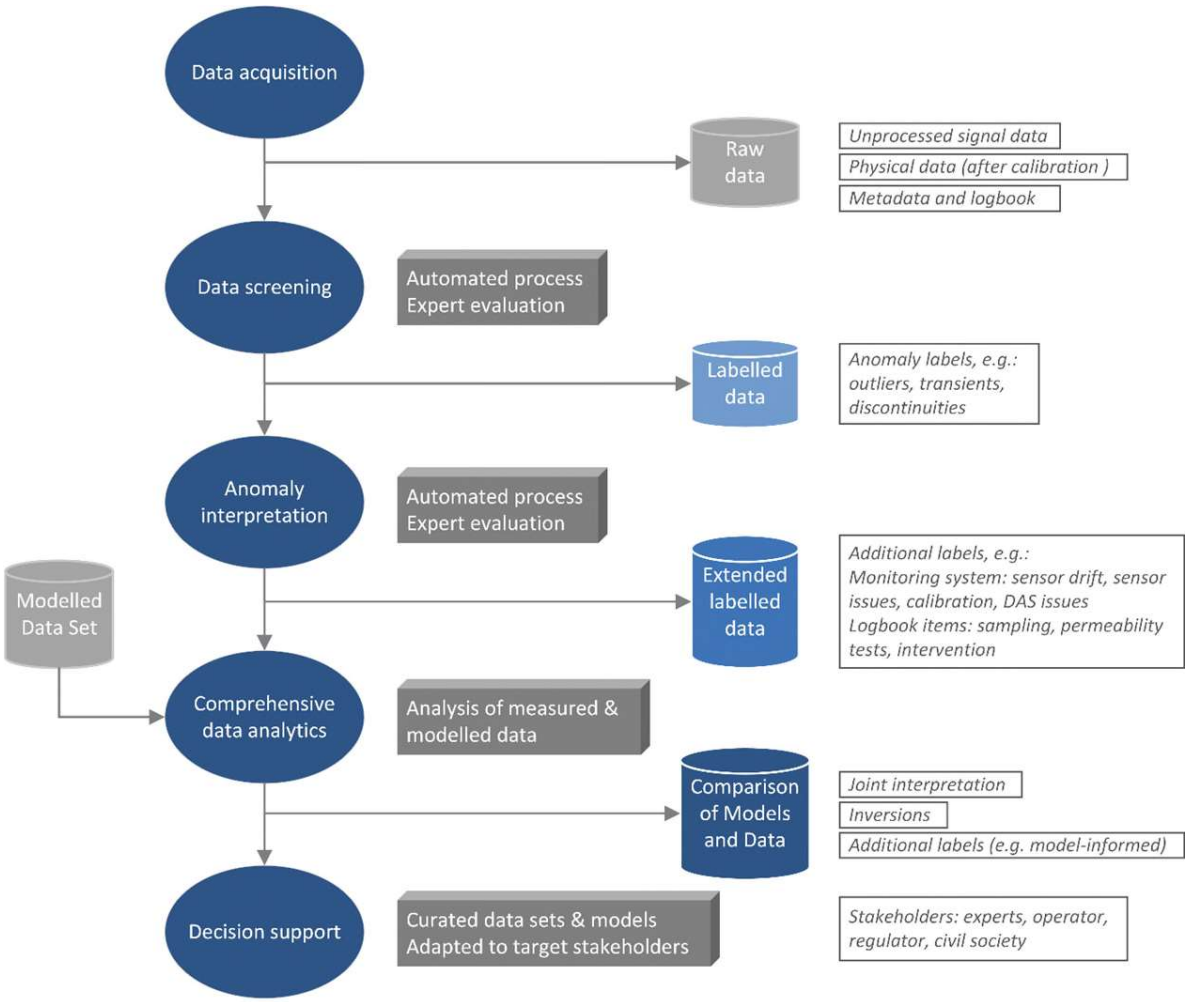


Figure 16 - Proposed workflow for data handling from acquisition to decision support

MODATS has provided developments that indicate how confidence in monitoring data can be achieved, and approaches that could be adopted within different programmes. Having an overall robust and reliable approach to the acquisition, management and use of monitoring data is the main way in which confidence can be built. The comprehensive approach adopted in MODATS contributes to this. Good management practices were identified for all aspects of the data lifecycle, including acquisition, management (processing and storage), use of the data (modelling) and communication of the data for decision making. The guidance provided from MODATS is generic and needs to be tailored to specific repository programmes, which respond to their specific boundary conditions. Tailoring the outcomes from MODATS to the specific context of each monitoring programme would provide a sound technical, scientific and sociological basis for developing and maintaining confidence in monitoring data.

4.2 EU-project PREDIS on Pre-disposal management of radioactive waste

EURIDICE contributed to WP7 of PREDIS. This work packages centres around 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 for 2 years. Monitoring is stopped, but postmortem analysis of the drums is planned for February 2025. A paper is being written on the results.

4.3 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 2025. 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 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. EURIDICE has also been involved in the reviewing of the overall IAEA report.

4.4 EURAD-2: European Partnership on Radioactive Waste Management

4.4.1 WP OPTI – HLW Repository optimisation including closure (strategic study)

EURIDICE is involved in Work Package 13 (WP13) – OPTI, which focuses on HLW repository optimisation, including closure. This work package is a strategic study. As outlined in the project description, the primary objective of this work package is to develop a mutual understanding and provide recommendations regarding methodologies and future activities for the design and optimisation of specific HLW deep geological repository systems, structures, components (SSCs), and procedures. EURIDICE is specifically involved in Task 4, which addresses key challenges related to the optimisation process of a repository and its components. On November 28, 2024, the kick-off meeting took place in Hannover alongside the Clay Conference. The meeting reviewed the strategic study's goals and featured presentations from representatives of WMOs, TSOs, REs, and CSEs, each sharing perspectives on optimization and key considerations. The next meeting within this work package is scheduled for January 24-25, 2024, in Delft. During this meeting, the first deliverable will be prepared. This is a green paper, which is a consensus view to stimulate discussion on topics that are of interest for the European Union. They typically contain a proposal that serve as a basis for a debate or a consultation process.

5 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 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.

5.1 Investigation of the long-term hydro-mechanical behaviour of the Boom Clay

This PhD was co-funded by ONDRAF/NIRAS and SCK CEN and is a joint collaboration with the "Laboratoire Navier/CERMES, l'École des Ponts ParisTech (ENPC)". The project was awarded to May Awarkeh, who started the research in October 2018 and completed it in November 2022, she had her public defence on January 4th 2023. 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 an 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.

5.2 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 project, initiated by SCK CEN and EURIDICE, and conducted in collaboration with l'École Nationale des Ponts et Chaussées (Laboratoire Navier/CERMES, Paris, France) and the University of Liège (Géotechnique, Urban and Environmental Engineering, Liège, Belgium). This 4-year research project began in October 2021 and is realised by Hassan Al Mais.

The primary objective of the study is to investigate the effects of saline solutions on the hydro-mechanical (HM) behaviour of Boom Clay. This research is of interest for the geological disposal of intermediate-level long-lived radioactive waste in Belgium, particularly bituminised waste known as Eurobitum. When this waste is placed in a geological disposal facility, it will come into contact with infiltrating groundwater. The increased amounts of highly soluble NaNO3 present in the waste will result in swelling of the waste, followed by dissolution and diffusion of the salt into the host formation. These processes result in two potential disturbances:

1. Geo-mechanical disturbances, caused by waste swelling and the consequent increase in pressure in and around the waste packages.
2. Chemical disturbances, due to the release of $NaNO_3$ and other soluble salts into the clay.

To examine these effects, an extensive experimental program, was carried out at Laboratoire Navier/CERMES. Thus, the influence of several saline solutions with different solute concentrations ((Na,Ca)NO3) and sodium occupancies (Na+) was examined by performing the following experiments:

- High-pressure oedometer tests.
- Swelling pressure tests.

- Chemical loading/unloading tests.
- Triaxial tests.
- Mercury Intrusion Porosimetry (MIP) to study the microstructure.

The experimental phase has been completed, and the findings have been disseminated through seminars, conferences, and working meetings. Additionally, two journal publications are currently being prepared for submission.

Based on the experimental findings, the primary parameters influenced by saline solutions were identified. These parameters served as inputs for the development of an Adapted two-surface Cam Clay model (ACC-2). This constitutive model will be implemented into the finite element code *LAGAMINE*, developed at the University of Liège. This integration is expected to enhance the understanding of the coupled chemical-hydro-mechanical (C-H-M) behaviour of Boom Clay. Following the validation of the model, a repository-scale analysis will be conducted to assess its applicability and performance in larger-scale scenarios.

5.3 Experimental investigation of the hydro-mechanical behaviour of Boom Clay at various depths

Until now, most of the knowledge on the behaviour of Boom Clay is essentially gained at a depth of 225 m in Mol, where the Belgium underground research laboratory (URL) HADES is located. Only a few tests were carried out at other depths or locations. As greater depths are being considered for a potential geological disposal facility in poorly indurated clays in Belgium, it is a challenge to transfer this knowledge gained at HADES URL level to greater depths and/or other locations.
To explore this topic, a PhD project was launched at ONDRAS/ NIRAS with ULiège and with the support of EURIDICE. The objective of this PhD project is to study the hydro-mechanical behaviour of Boom Clay from cores taken at other depths than the depth of the HADES URL and compare the obtained results as a function of the depth. Especially, cores from about 300-400 m in depth, obtained from a recent core drilling, will be investigated. Additionally, specimens collected at outcrops and at the depth of the HADES URL will also be tested to deduce a trend on the effect of the depth on the hydro-mechanical behaviour of Boom Clay. The experimental results obtained during this project will complement the existing knowledge. The outcomes of the project will allow one to evaluate the transferability of the data gained at the HADES URL level (225 m) towards greater depths and so, will contribute to the assessment of the feasibility and the long-term performances of geological disposal facilities, in the perspective of being constructed in the Boom Clay formation at around 400 m in depth. The PhD project commenced in 2023 and will span six years, as the PhD candidate, Sophie De Kock, also holds a position as an assistant.

5.4 Experimental and numerical characterisation of the mechanical anisotropic properties of Boom Clay

Recent observations have shown that the mechanical anisotropy of Boom Clay and the anisotropic *in situ* stress states significantly influence the deformation modes of galleries (Dizier et al., 2023; Dizier and Georgieva, 2024). Over time, gallery deformation increases due to the viscoplastic behaviour of the clay, which leads to a progressive increase of the load on the lining. This load continues to rise even after decades of observation. Understanding Boom Clay's anisotropic properties and its long-term behaviour is important for optimizing the support design of a future deep geological repository.

To address these challenges, a scientific research project titled *"Investigation of the Long-Term Behaviour of Boom Clay"* was conducted as a joint PhD effort between SCK CEN, EURIDICE, NIRAS/ONDRAF, and ENPC from 2018 to January 2023. The primary objective of this PhD was to enhance the understanding of Boom Clay's long-term behaviour through an experimental program and the development of a relevant constitutive model.

Building on this foundation, the current project focuses on the anisotropic behaviour of Boom Clay, specifically its mechanical plastic anisotropy. It has started in December 2024 and is planned to be carried out in two phases. The first phase involves an experimental program using triaxial tests with varying orientations to the bedding planes and under different confining pressures. The goal is to characterise the mechanical plastic anisotropy and use this data to develop a new constitutive model capable of accurately simulating the excavation process and the thermo-hydro-mechanical behaviour of Boom Clay. In the second phase of the project, the constitutive law will be implemented in a finite element code to simulate *in situ* experiments, such as the excavation of the main galleries of the underground research laboratory (URL). The model's predictions will be compared against *in situ* data collected over the past two decades. This PhD is a joint research project between SCK CEN, EURIDICE, NIRAS/ ONDRAF and ULiège which started the 1st of December 2024. The PhD student who will perform this work is Nemanja Glusica.

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Operation and safety of installations

The primary task of the Operations and Safety team is the maintenance of 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. The Operation and Safety process is overseen by the Consultation Committee on Safety, Health, Environment and Security (OC VGMB), which meets monthly.

In the first half of 2023, knowledge transfer was ensured since one of our long-term technicians went on well-deserved retirement after 40 years of service. Our newer technical employees performed core drillings (Section 1.3) and replaced a hoisting rope (Section 3.2) for the first time. To guarantee and ensure the operation and safety of the HADES URL, the following activities were conducted in 2023-2024.

1 Technical support for RD&D

1.1 EURIDICE projects

The Operations and Safety team gives technical support to RD&D activities for different projects within EURIDICE. A non-exhaustive list is shown here. The RD&D project on the stability of the gallery linings is discussed in more detail.

- 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.
- …

1.1.1 Stability lining galleries

Because of the visual degradation of the lining in the Test Drift, EURIDICE scientists have done a lot of research and analytical work over the past 2 years on the stability of the lining (Figure 17). This analytical work is very important to ensure the safe operation of HADES. In addition, the understanding of the interaction between the lining of the galleries and the Boom Clay, is an important aspect for the feasibility of a geological disposal facility. This was done in support of the RD&D project on the stability of the galleries (Section 2.1).

Figure 17 - Mapping of the lining of the test drift.

Through a thorough collaboration between the technicians and scientists of EURIDICE a lot of work has been done in:

- Identifying and mapping the current damages in the lining.
- Scaling and cleaning the lining.
- Performing visual inspections and creating a complete documentation with pictures of the Test Drift.
- Follow up of the crack meters installed in strategic places.
- Accompanying and supporting external workers with the 3D scan and the topographical measurements.

1.2 Supporting third-party research

1.2.1 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.
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 JRC-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. Some key projects of JRC-Geel in 2023-2024 included:

- Characterisation of reference materials for food safety (shrimp and mushroom) and radioprotection (building materials).
- Detecting radio-impurities in reference materials for nuclear decay data measurements.
- Radiotracer studies of water from the Pacific Ocean to determine ocean mixing, in order to build reliable climate models.
- Detecting radiocesium in individual organs of large wild animals; bear and wolf. (A consequence of the new Basic Safety Standards that takes up radioprotection of flora and fauna for the first time).
- Measurement of rare nuclear decays.
- Measurements of natural radiotracers in sediments to study gravity-driven groundwater flow systems.
- 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.

1.2.2 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 for the LEGEND-200 experiment), at the underground Laboratori Nazionali del Gran Sasso (LNGS) in Italy. All 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 EURIDICE team.

This LEGEND collaboration has recently received strongly favourable high level science evaluations. As a consequence, it has just been awarded significant funding from the USA and Europe to continue to build the LEGEND-1000 experiment. It will contain 1000 kg of Ge-detectors. Discussions on how to realise the future characterisation campaigns in HADES have commenced.

1.3 Core drilling

A new core drilling of more than 20 meters through the concrete wall of the Connecting Gallery and into the clay was carried by the entire EURIDCIE team. New fresh Boom Clay samples for research purposes were obtained.

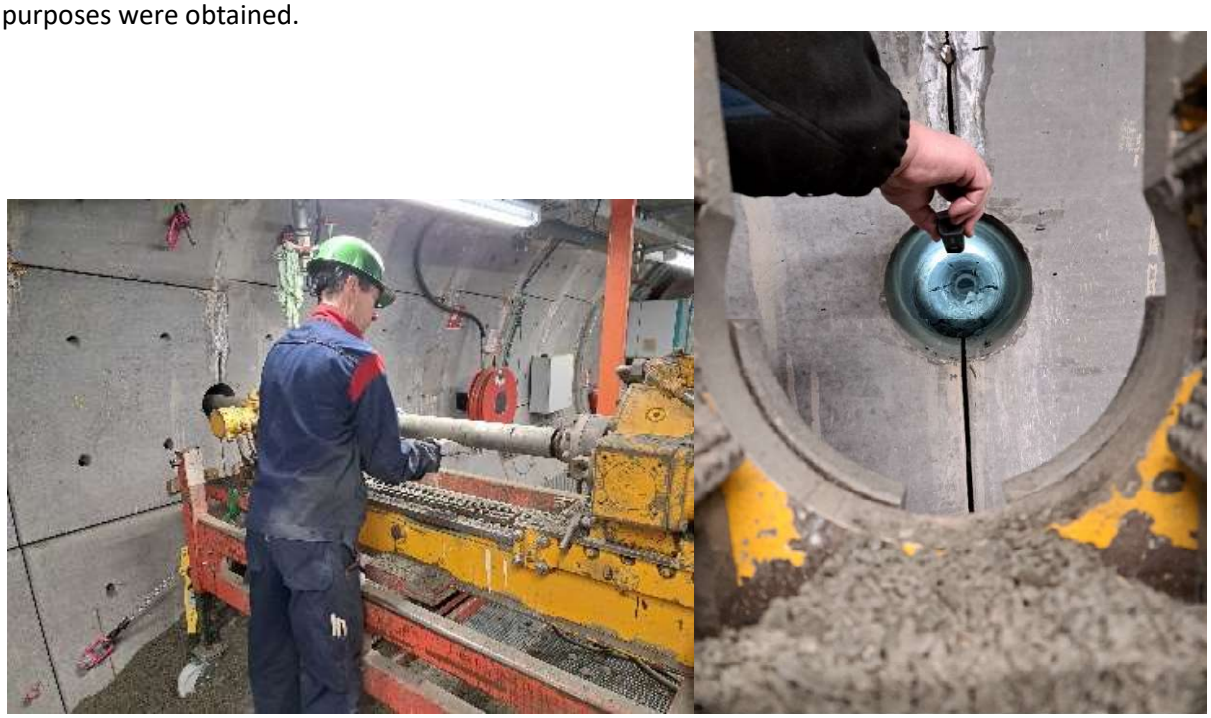


Figure 18 - Core drilling in the connecting gallery in March 2023

1.4 Lithoteek

The unique “lithoteek” of clay cores was optimised.

Figure 19 - Newly organised lithoteek with clay cores from regional drillings and boreholes

2 Support to Communication

2.1 Demo hall

Old machinery used for excavation and exploitation of HADES (old hoist installation of shaft 1 and tunnel boring machine for PRACLAY) are exhibited together with the mobile expo to complement the current exhibition.

[photo to be included]

2.2 Assistance to visits

A green helmet – technician of EURIDICE has to accompany each group of maximally 9 visitors in the hoisting cage and in HADES. Moreover, a machinist with adequate training has to remain above ground during visits as all times, in case of emergency or problems with the hoisting mechanism. Given the roughly 80 group visits per year, this requires quite some effort from the Operation & Safety team.

3 Maintenance, controls and inspections installations

Periodic inspections and preventive maintenance are required and essential to ensure the operation of the installations and the safety of employees and visitors on the site. Therefore, EURIDICE technicians and AIB Vinçotte spend significant time carrying out those inspections according to the established inspection and control programme.
In the end of 2023, the frequency converter of the emergency hoist installation of Shaft one failed. Because of compliance with German mining legislation, it was very difficult to get the frequency converter repaired. Finally, a new converter was purchased and installed by a German company. Based upon our experience we built since the renovation project shaft one, the high dependence on German contractors in case of a failure was once again demonstrated.

3.1 Energy saving measures

A complete conversion from fluorescent to LED was done in the offices, atelier and machine hall. As a result of the energy audit and some technical difficulties, the old (inefficient) heating system for the Demo Hall and EUR 1 offices was replaced with a new heating system with separate circuits. Moreover, research was done and proposals were formulated for other energy-saving measures in the coming years.

3.2 Replacement of the rope

The 20-year-old rope of the emergency cage of the second shaft was replaced. An important replacement to ensure safety.

Figure 20 - Replacing the rope in the ventilation building.

4 Safety on site

4.1 Consultation Committee on Safety, Health, Environment and Security

The Consultation Committee on Safety, Health, Environment and Security, referred to as the OC VGMB (see section Organisation in the chapter 'EURIDICE today') 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.

4.2 Evacuation/Emergency exercises

With activities in a laboratory 225 m in the underground next to the nuclear site of SCK CEN, it's essential that everyone prioritises safety and knows what kind of role he/she needs to fulfil in case of emergencies. In 2024, 2 large-scale emergency exercises were organized for EURIDICE employees and the internal fire department SCK CEN. These exercises are needed to evaluate the current emergency procedures and which lessons we have learned for improvement in the future.

Figure 21 - Emergency and evacuation exercises

Based on the outcome of these emergency exercises, the safety protocols were re-evaluated and adapted for the workers and visitors in HADES.

5 Other projects of O&S

5.1 Water entrance into the First Shaft

After the refurbishment of the First shaft, new leaks were found at various depths during the shaft inspections. This water entrance may have a negative impact on the service life of the new hoist installations.

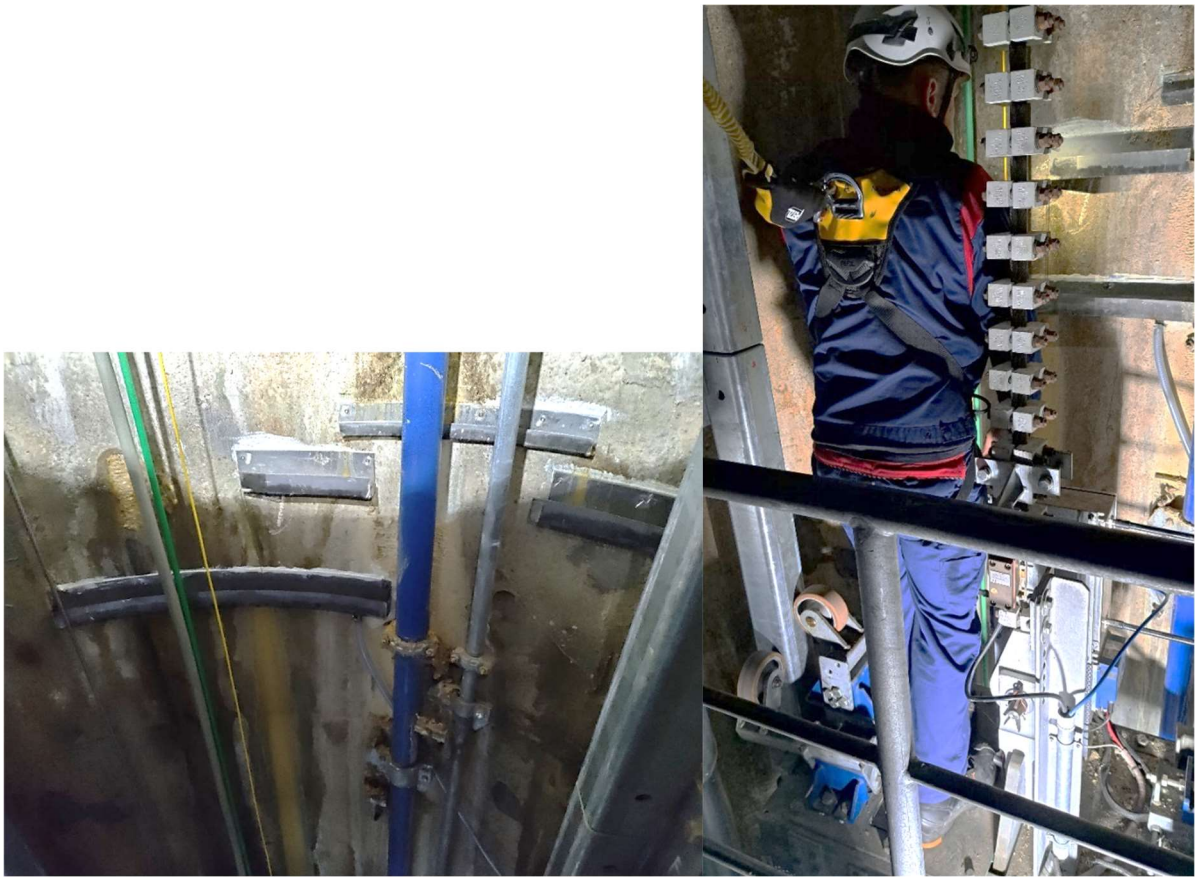


Figure 22 - Water infiltration in shaft 1.

To monitor, quantify and control the water entering shaft 1, drainage systems were installed in the shaft at 120 m and 196 m depth. Both leaks remain more or less stable and have flow rates of 2.2 l per hour and 1.4 l per hour, respectively.

A 3D scan was also performed where all points of water ingress were mapped. In this way, we are able to monitor changes in water entrances and identify potential new spots.

5.2 Refurbishment/renovation of the main and emergency hoist installations of the second shaft

The current, second hand, hoist installation (1993) was reinstalled at EURIDICE in the end of the 90' by a consortium of Deilmann-Haniel GmbH - NV Smet Boring - Wayss & Freytag AG to excavate the Second shaft to a depth of 230 m.

After the excavation of the shaft, the installation was equipped with a personnel cage. Additional safety devices and an emergency hoist installation were installed to enable an automatic operation. In a later phase the installation was also used for the excavation of the Connecting Gallery (2001-2002) and the PRACLAY Gallery (2007).

The main and emergency hoist installations are more than 20 years old. The installation as such is currently safe, but it is outdated. Spare parts are no longer available for several critical components and the control system is no longer supported. If we want to continue to ensure a safe and a reliable main access to the underground laboratory, a renovation is necessary. This was also the case for the First shaft.

In the past, the underground laboratory was considered as a mine. At that time, the installations were built to comply with the old Belgian (and German) mining legislation. After the renovation of the hoist installations at the First shaft the operation license of EURIDICE was changed by Federal Public Service for Employment, Labour and Social Dialogue. All references/requirements to the abolished Belgian mining legislation were deleted from the license. The license is now based on the general requirements of the CODEX. The removal of this legislation does not affect the current installation, but must be taken into account in future adjustments and refurbishment of Shaft 2.

Figure 23 - Hoisting installation of the First Shaft.

Over the years, the need to update the hoisting installation of the second Shaft became more and more clear. To this end, a public tender for a limited renovation of the hoist installation at the Second shaft was launched in the previous period. In 2023 however, we were forced to stop this public tender. The purpose of this tender was to renovate/change only the critical (safety) components, but potential tenderers pointed out that given the lack of regulations in Belgium for such an installation, it was too risky for them to present an offer and proceed with the works. It was also unclear to them whether the works could be limited to the requested scope as the compatibility between existing and potentially new equipment could not be guaranteed. As a result, the tendering process was interrupted, and a risk assessment was launched in order to understand the shortcomings of the installation against the applicable European regulations and the requirements to comply with CODEX

as described in the operating license. This risk assessment resulted in a number of actions that have been and are being implemented according to the priorities.

In 2024, it was decided to prepare a major renovation according to European regulations (Machinery Directive/Regulation). Together with ONDRAF/NIRAS, we restarted a market research with potential candidates and to determine the right strategy of the renovation and public tender.

At this moment we expect to carry out the renovation project in 2027.

Communication

Communication on its activities is one of EURIDICE's statutory tasks. The HADES URL is a powerful tool for explaining the research on geological disposal in poorly indurated clays and is as such the most convincing infrastructure for the public acceptance of a deep geological disposal facility. A visit to the underground laboratory is the best way for visitors to get an idea about the concept of geological disposal (Figure 24). Since the opening of the visitor centre Tabloo in Dessel, visits to HADES are limited to technical-scientific actors and those who play an important role in the decision-making process for geological disposal, whereas before the COVID-19 pandemic, secondary schools and all socio-cultural groups were welcomed. The latter are now redirected to Tabloo, which has been very successful at attracting a large audience over the past years. The groups that now visit HADES are exclusively from universities, other trainings, waste management organisations and research institutes, political stakeholders, etc. This led to the decision that the visits are exclusively guided by the EURIDICE personnel.

In addition to arranging visits to HADES, EURIDICE has its own website[1], organises the annual Exchange Meeting which is open to external audience, internal talks on the research that is relevant within the PPP between the partners, and also publishes reports, web articles and LinkedIn and other social media posts through the channels of the members. The goal is to inform a wide audience about its activities within the context of the Belgian programme on geological disposal.

The communication strategy for 2021-2025 was defined in interaction with both members through the OC Communication that gathers monthly and steers in function of the needs of both members. This strategy focuses on three main objectives: informing stakeholders about the research activities or EURIDICE, showcasing how these activities support responsible waste management, and supporting the communication efforts of SCK CEN and NIRAS.

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

Figure 24 – University students visiting the HADES URL

1 Visits

In 2023, we welcomed a total of 1040 guests, over 77 groups, to EURIDICE and the HADES URL. In 2024 we received a very comparable number of 1058 guests split over 80 groups. Through such visits, we aim to foster transparency, build trust among stakeholders, and contribute to a broader understanding of the scientific and technical basis for geological disposal as a sustainable and responsible solution. These groups included students of both Belgian and foreign universities and colleges, new employees of SCK CEN and ONDRAF/NIRAS, collaborators in the nuclear field and political stakeholders. Several of these visits took place within the framework of the societal debate "Now for Tomorrow," which was organised at the initiative of NIRAS by the King Baudouin Foundation. This debate originated from the Royal Decree of October 2022 (see Chapter "EURIDICE: History, Tasks, and Fields of Expertise"). As part of this initiative, two schools—one from the Flemish Region and one from the Walloon Region—that had participated in the societal debate paid a visit to the HADES underground research laboratory. Additionally, staff with expertise in subsurface studies from the Flemish, Walloon, and Brussels regions also visited the facility (Figure 25).

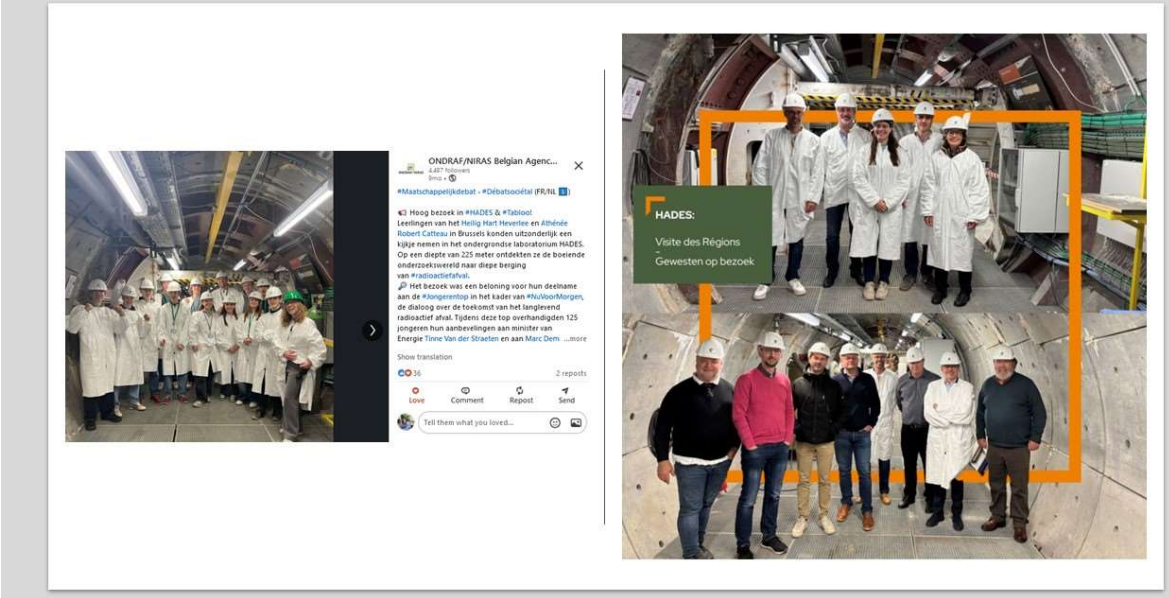


Figure 25 - Visits within the frame of the societal debate 'Now for Tomorrow'.

The emphasis on stakeholder involvement and the communication of geological disposal as a solution for radioactive waste management is not unique to Belgium. Our neighbouring countries, including the Netherlands, are experiencing a similar trend. From this international context, we welcomed several visitors with a professional interest in this field.
A visit to HADES remains a very convincing and effective tool to demonstrate what geological disposal entails and to showcase how decades of research have contributed to the development of a safe and reliable option for the long-term management of radioactive waste.

Guiding of these visits was mostly done by EURIDICE staff. The ONDRAF/NIRAS guides (formerly Isotopolis guides, currently Tabloo) were only booked in case the EURIDICE staff was not available. Since the types of groups have evolved from general public to specific profiles in the field of radioactive waste, we have opted to guide the visits ourselves.
Since its opening in March 2022, Tabloo is integrated in most visits to the HADES URL. It is often the starting or end point for stakeholders that visit EURIDICE. While Tabloo is the main communication tool on radioactive waste management and nuclear research at SCK CEN, 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.

Overall appreciation of the visits is always very high. All groups are very pleased with the explanations and the unique infrastructure.
In December 2023, a problem with the hoisting cage of shaft one arose. This technical issue was resolved in March 2024, meaning that many visits had to be rescheduled, and three visits could not be organised (see section 4.2 of chapter 'Operation and Safety'). We did our absolute best to organise suitable visits for all the groups that requested one. No other technical problems interfered with the visits in 2023 and 2024.

2 Newsletters

From the Exchange meeting account, an external newsletter was published on March 7th 2023 on two themes:

1. The publication of the activity report 2021-2022, which was made available on the EURIDICE website as well.
2. The publication of the special issue "*Geological Disposal of Radioactive Waste in Deep Clay Formations: 40 Years of RD&D in the Belgian URL HADES*", edited by X.L. Li, M. Van Geet, C. Bruggeman and M. De Craen and published by the Geological Society London (see Scientific output). This Special Publication presents the main contributions of the HADES laboratory to Belgian and international research into geological disposal. Its availability in open access was highlighted in this newsletter.

A second external newsletter was published on March 13th 2024, again on the special issue of 40 years of HADES. This newsletter informed the public about that after one year of being available in Open Access, the special issue was downloaded over 4000 times and 150 printed copies had been sold, which is a great result according to the Geological Society London.

In 2024, four newsletters were published by the account PPP-talks, targeting the collaborators of ONDRAF/NIRAS, SCK CEN and Belgoprocess who are part of the PPP. This is also managed by the EURIDICE communication manager. These newsletters are drawn up with input from the coordination committee of the PPP, within its domain communication that has adopted the EURIDICE communication strategy of 2021-2025.

3 Exchange Meetings

Since 2023, the consultation committee communication decided that the Exchange Meetings are to be organised once per year as full-day events at Tabloo, in autumn. The topic of the Exchange Meeting is decided by the PPP coordination committee in the beginning of the year. The goal is to make it a strong brand, broadly inviting all technical-scientific and political stakeholders in the field of radioactive waste management, and to highlight achievements of the Belgian Programme towards a final waste disposal. To this end, the list of invitees was updated by both SCK CEN and ONDRAF/NIRAS. For example contacts from the Flemish, Walloon and Brussels Regions were added to the list, as well as stakeholders that were identified through the societal debate organised by the King Baudouin Foundation on the initiative of ONDRAF/NIRAS (Nu voor Morgen, Présents pour le Futur).

3.1 25th Exchange Meeting on category A surface disposal

The 25th Exchange Meeting was organised on Tuesday the 10th of October 2023. Over 160 people registered for this event, while 110 people attended. The programme consisted of eight presentations on the category A surface disposal project, focussing on the safety concept, performance analysis, hydrogeological aspects, the construction, disposability of the category A waste and role of FANC and BelV in this project. Site manager Rudy Bosselaers concluded the meeting with his prospects.

The meeting was well received, with attendance of both professionals as other interested parties.

3.2 26th Exchange Meeting on Belgian achievements within EURAD-1

On October 25th 2024, the 26th Exchange Meeting was organised on the topic of EURAD, focussing on the Belgian achievements within this European programme. The goal of this Exchange Meeting was to highlight the Belgian achievements in EURAD-1 (the European Joint Programme on Radioactive Waste Management), focusing on why it is important to participate as Belgian actors and what this kind of collaboration adds to the Belgian programme. It was not the intention to discuss all the separate (Belgian) contributions but rather to present the project as a whole. EURAD is a very broad research

programme, and the densely packed schedule of the Exchange Meeting shows the impressive number of contributions to EURAD. There was Belgian involvement in all work packages as well as in the sister program PREDIS. All work packages and the outlook of EURAD-2 were presented.
130 participants registered for this event, of which 110 attended. The participants were impressed with the Belgian involvement to EURAD, however time management and clear instructions were lacking, making this a learning point for future events.

4 Participation in external events, conferences and meetings

In 2023 and 2024, EURIDICE staff participated in the following external events, conferences and meetings:

4.1 IAEA meetings in 2023 and 2024

EURIDICE represented Belgium at the IAEA URF Network meetings in April 2023, April 2024 and June 2024. 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.

4.2 NEA Clay Club meetings in 2023 and 2024

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 yearly meetings in 2023 and 2024.

4.3 Clay Conference 2024

EURIDICE scientists presented their work at the 9th International Conference on Clays in Natural and Engineered Barriers for Radioactive Waste Confinement, November 2024, Hannover, Germany. This Clay Conference provides a unique networking platform for sharing scientific and technological knowledge. Two oral presentations were given at the conference, one on PRACLAY modelling by Guillaume Flood-Page, and on Long-term soil-structure interaction and overall stability of the galleries in HADES by Temenuga Georgieva. Both were well-received at the conference. Moreover, HADES-related research on the NEMESIS experiment was also presented at the conference.

4.4 BVOTS/ABTUS

BVOTS-ABTUS (Belgische Vereniging voor Ondergrondse Technieken en Stedenbouw / Association Belge des Techniques et de l’Urbanisme Souterrains) promotes the knowledge about the study and the realisation of underground works of all kinds: transport tunnels (road, metro and rail), sewers and technical galleries, shopping centres, car parks and underground factories, main underground structures as power and storing plants, etc.

As such, participation in this association is interesting for all sectors of science and technique linked with problems as stability of underground works, construction techniques, organisation of underground works, specific material for these works, classical and spatial town planning, knowledge of the environment, juridical and administrative aspects, economic and social questions, etc. EURIDICE scientific staff participate in this association by means of lateral visits and exchanges through seminars and presentations.

5 Media coverage

5.1 General

5.1.1 Article RTBF

On March 28 2023, a news crew of the Walloon tv channel RTBF visited HADES. This resulted in a news article in which HADES and the PRACLAY experiment were prominently featured.
https://www.rtbf.be/article/enfouissement-des-dechets-nucleaires-le-chantier-du-siecle-au-budget-incertain-11175509

5.1.2 Reportage Nieuwsuur

In April 2024, the Dutch current affairs program Nieuwsuur visited HADES for their article on geological disposal. This resulted in a short news item in which HADES was briefly featured.
https://nos.nl/nieuwsuur/artikel/2519652-advies-aan-kabinet-maak-haast-met-plan-voor-opslag-kernafval

5.1.3 Podcast Splijtstof

In the Dutch podcast series 'Splijtstof', by Dutch science communicator Diederik Jekel and tv presenter Daan Nieber, HADES played a key role in the fourth episode on radioactive waste. The duo visited our underground facility and featured the sounds of the hoisting cage and an interview with our communication manager on their podcast. The segment on HADES ended with the words 'what can I say, Belgium is awesome'. The podcast was launched on October 22nd 2024 and has a 4.9 star rating based on 127 votes. SCK CEN, ONDRAF/NIRAS and EURIDICE were also mentioned in a well-liked LinkedIn post of Diederik Jekel (Figure 26).

Figure 26 - LinkedIn post Diederik Jekel on his visit to HADES while recording his podcast 'Splijtstof'.

5.2 Socials

In the communication strategy of EURIDICE, it is clearly worked out that external communication is done through the members to avoid confusion and since EURIDICE is not a strong brand. This is also

the case for LinkedIn posts and other social media. A number of HADES research-related posts were published in 2023 and 2024 (.

- Start of the NEMESIS experiment in HADES (published in September 2023 on LinkedIn by SCK CEN and by ONDRAF/NIRAS in a LinkedIn post on the highlights of 2023)
- Celebration of 1 year of the NEMESIS experiment (published in October 2024 by both SCK CEN and ONDRAF/NIRAS on LinkedIn)
- 10 years of the PRACLAY heater test (published in November 2024 on Facebook and in December 2024 by ONDRAF/NIRAS on LinkedIn)
- Celebration of 1000th visitor to HADES (published in December 2024 by SCK CEN on LinkedIn)
- Clay Conference contributions of the scientific staff (LinkedIn campaign with set up by EURIDICE communication, 3 posts on different topics published in November 2024 by SCK CEN and ONDRAF/NIRAS on LinkedIn)

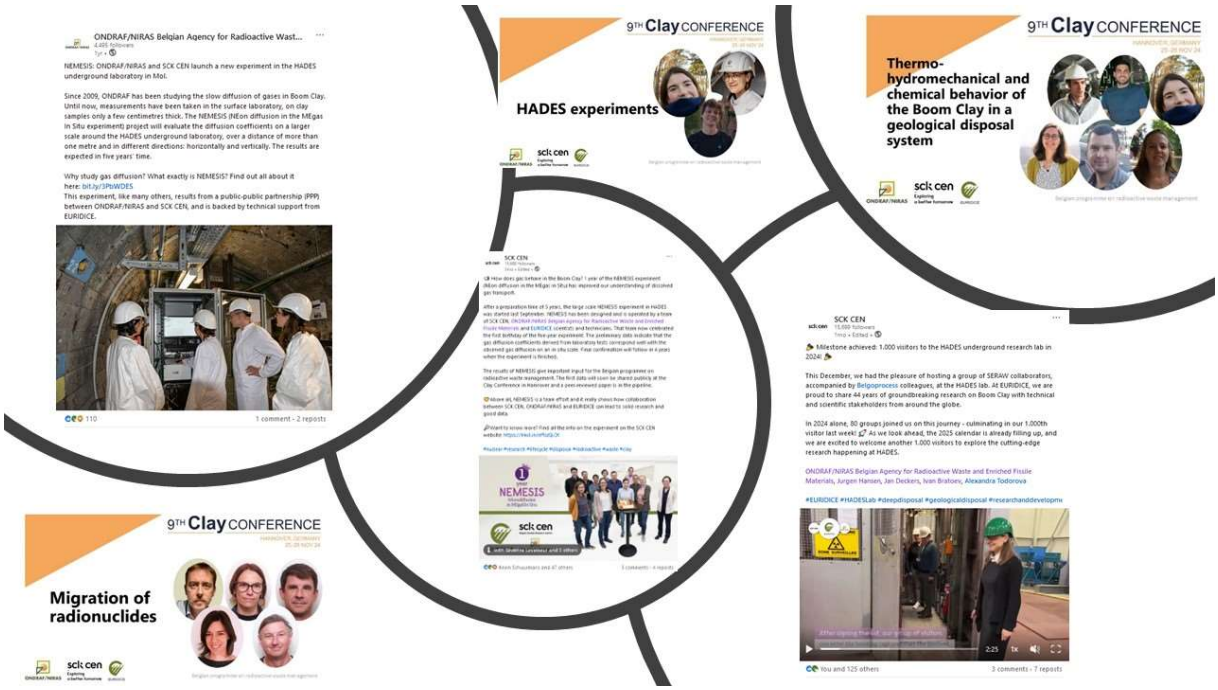


Figure 27 - Some LinkedIn posts prepared by EURIDICE in 2023-2024.

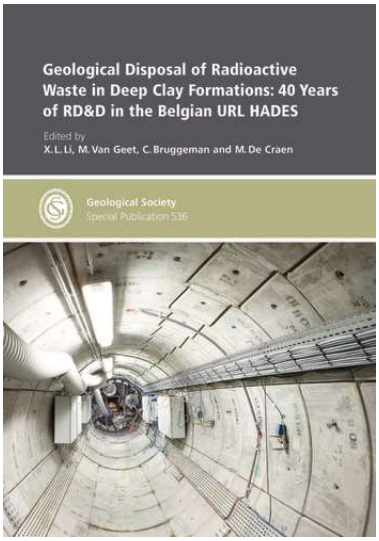
6 Exhibition

From January 2023 until April 2024 (it was prolonged for 4 months), an exposition on waste and garbage was organised by the province of Liège (Figure 28). This exposition was called ORDURES and addressed the major ecological, social and economic issues generated by our waste to understand its nature, its dangerousness, its treatment and its impact. On the initiative of ONDRAF/NIRAS, a waste drum and barrel of the EURIDICE demo hall were made available for this exposition.

Figure 28: Poster of the exhibit on waste organised by the province of Liège.

Scientific output

1 SPECIAL PUBLICATION on 40 years R&D in the HADES URL



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).

The following papers are published in the HADES's 40th anniversary Special Publication:

Geological disposal of radioactive waste in deep clay formations: 40 years of RD&D in the Belgian URL HADES. Van Geet, M., Bruggeman, C. & De Craen, M., 24 Aug 2023, In: Geological Society, London, Special Publications. 536, 1, p. 1-10 10 p., 1.

The role of the HADES URL in better understanding of the Boom Clay pore water geochemistry. De Craen, M., Moors, H., Honty, M. & Van Geet, M., 27 Feb 2023, In: Geological Society, London, Special Publications. 536, 22 p., 93.

Forty years of investigation into the thermo-hydromechanical behaviour of Boom Clay in the HADES URL. Li, X. L., Dizier, A., Chen, G., Verstricht, J. & Levasseur, S., 27 Feb 2023, In: Geological Society, London, Special Publications. 536, 16 p., 103.

Characterization of Boom Clay anisotropic THM behaviour based on two heating tests at different scales in the HADES URL. Chen, G., Li, X. L., Dizier, A., Verstricht, J., Sillen, X. & Levasseur, S., 27 Feb 2023, In: Geological Society, London, Special Publications. 536, 24 p., 72.

Gas transport in Boom Clay: the role of the HADES URL in process understanding. Jacops, E., Yu, L., Chen, G. & Levasseur, S., 20 Feb 2023, In: Geological Society, London, Special Publications. 536, 1, 18 p.

Lessons learned from *in situ* corrosion experiments in the HADES URL. Kursten, B., Caes, S., De Souza, V. & Gaggiano, R., 20 Jun 2023, In: Geological Society, London, Special Publications. 536, p. 93-130 38 p.

CP1 and Tribicarb-3D - unique long-term and large-scale *in situ* migration tests in Boom Clay at the HADES Underground Research Laboratory. Aertsens, M., Weetjens, E., Govaerts, J., Maes, N. & Brassinnes, S., 5 Sept 2023, In: Geological Society, London, Special Publications. 536, p. 131-144 14 p.

Coupled flow and transport modelling of a large-scale *in situ* migration experiment with 14C-labelled natural organic matter colloids in Boom Clay. Govaerts, J., Maes, N., Durce, D., Aertsens, M. & Brassinnes, S., 1 Sept 2023, In: Geological Society, London, Special Publications. 536, p. 145-158 14 p.

The construction of the HADES underground research laboratory and its role in the development of the Belgian concept of a deep geological repository. Li., XL, Neerdael B., Raymaekers D., and Sillen X., 20 Feb 2023, In: Geological Society, London, Special Publications. 536, p. 145-158 14 p.

Stability analysis and long-term behaviour of deep tunnels in clay formations. Dizier, A., Scibetta, M., Armand, G., Zghondi, J., Georgieva, T., Chen, G., Verstricht, J., Li, X. L., Leonard, D. & Levasseur, S., 27 Feb 2023, In: Geological Society, London, Special Publications. 536, 20 p., 86.

Assessment of long-term sensor performance based on a large THM experiment in the HADES URL. Verstricht, J., Nackaerts, D., Li, X. L., Leonard, D., Levasseur, S. & Van Geet, M., 27 Feb 2023, In: Geological Society, London, Special Publications. 536, 19 p., 87.

Forty-five years of joint research programmes on geological disposal of radioactive waste and the pioneering role of the HADES Underground Research Laboratory. Hassine, S.B.F., Davies, C., & Garbil R., 17 Feb 2023, In: Geological Society, London, Special Publications. 536, p. 225-236 11p.

Contribution of HADES URL to the development of the Cigéo project, the French industrial centre for geological disposal of high-level and long-lived intermediate-level radioactive waste in a deep clay formation. Armand, G., Plas, F., Talandier, J., Dizier, A., Li, X. L. & Levasseur, S., 27 Feb 2023, In: Geological Society, London, Special Publications. 536, 1, 20 p., 98.

25 years of cross-fertilization between HADES and Mont Terri rock laboratory. Nussbaum, C., Bernier, F., Bleyen, N., Bossart, P., Bruggeman, C., De Cannière, P., Fierz, T., Neerdael, B., Valcke, E. & Volckaert, G., 9 Mar 2023, In: Geological Society, London, Special Publications. 536, 1, 29 p.

Underground research laboratories, an important support to the Belgian Regulatory Body's Research and Development programme and the management of uncertainties. Bernier F., Detilleux V., Lemy F., Pochet G .M., Surkova, M., Volckaert, G. & Mommaert C., 20 Feb 2023, In: Geological Society, London, Special Publications. 536, P. 287-295 8p.

Important roles of underground research laboratories for the geological disposal of radioactive wastes: an international perspective. Mayer, S.J., Van Marcke, P., Jung, H., Thompson, P. and Acharya, G., 14 June 2023, In: Geological Society, London, Special Publications. 536, p. 297-309.

Making the future in the present: using Science and Technology Studies to reflect on 40 years of research in the HADES Underground Research Laboratory. Geysmans, R., Silvikko De Villafranca, M., & Meskens G., 9 Jan 2023, in Geological Society, London, Special Publications. 536, p. 311-320.

2 OTHER JOURNAL PAPERS

Boom Clay pore-water geochemistry at the Mol site - Chemical equilibrium constraints on the concentrations of major elements. Wang, L., Honty, M., De Craen, M. & Frederickx, L., 1 Jan 2023, In: Applied Geochemistry. 148, 19 p., 105541.

Retour sur l'analyse de la stabilité d'une galerie construite dans une argile faiblement indurée à 225 m de profondeur dans le laboratoire souterrain HADES à Mol, Belgique: Feedback on the stability analysis of a gallery built in a poorly indurated clay at 225 m in the HADES Underground Research Laboratory in Mol, Belgium. Dizier, A., Scibetta, M., Georgieva, T., Li, X. L. & Levasseur, S., 1 Apr 2023, In: Tunnels et Espace Souterrain. 284, Avril-Mai-Juin 2023, p. 106-110 6 p.

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Model order reduction of nonlinear thermo-hydro-mechanical systems by means of elastic and plastic domain sub-structuring. Larion, Y., Massart, T. J., Díez, P., Chen, G., Seetharam, S. & Zlotnik, S., 15 Oct 2024, In: Finite Elements in Analysis and Design. 239, 17 p., 104205.

3 REPORTS

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Automation of the calibration process: Introduction and lay out of the project. Nackaerts, D., 2024. (EURIDICE-T-1003).

Calibration of pore pressure transmitters in HADES URL: Year report 2022 (including PRACLAY pressure transmitters). Nackaerts, D., & Olijslagers, B., 2023. (EURIDICE-T-0924).

Environmental monitoring in HADES: Year report 2022. Verstricht, J., 2023. (EURIDICE-T-0934).

Monitoring in support of the THM studies (CG lining stability): strain gauges and topographic survey: Year report 2023. Nackaerts, D., & Olijslagers, B., 2024. (EURIDICE T-1040).

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PRACLAY: Trimestral Synthesis of Unexpected Maintenance Activities: № 32: 01.11.2023 - 31.01.2024. Georgieva, T., Nackaerts, D., Olyslaegers, G., & Verstricht, J., 2024. (EURIDICE T-1071).

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Effect of salt concentration and sodium occupancy on the swelling behaviour of Boom Clay. Al Mais, H. Day of the PhDs 2023 at SCK CEN, Mol, Belgium.

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Nemesis - neon diffusion in MEGAS *in situ* experiment. Jacops, Elke; Vanleeuw, Anneleen; Yu, Li et al. SEG – 2023, Delft, Netherlands.

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5 THESES

Investigation of the long-term behaviour of Boom Clay. Doctoral thesis by Awarkeh, M. Mentored by, Dizier, A., & Yu, L., 2023 Ecole des Ponts ParisTech.

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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
IAEA	International Atomic Energy Agency
MODATS	MOnitoring equipment and DAta Treatment for Safe repository operation and staged closure
Modern2020	Development and Demonstration of monitoring strategies and technologies for geological disposal (within the framework of the Horizon 2020 Euratom Work Programme)
NEA	Nuclear Energy Agency
NEMESIS	Neon diffusion in MEgaS installation In Situ
ONDRAF/NIRAS	Belgian Agency for Radioactive Waste and Enriched Fissile Materials (BE)
PRACLAY	Preliminary Demonstration Test for Clay Disposal
PPP	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