Underground research laboratories, an important support to the Belgian Regulatory Body's Research and Development programme and the management of uncertainties

Frédéric J. Bernier[1]*, Valéry Detilleux[2], Frank Lemy[2], Guillaume M. Pochet[1], Maryna Surkova[1], Geert Volckaert[1] and Chantal Mommaert[2]

[1]Waste Management and Disposal, FANC, Brussel 1000, Belgium

[2]Bel V, Brussel 1070, Belgium

FJB, 0000-0003-4945-7215

*Correspondence: frederic.bernier@fanc.fgov.be

Abstract: In order to fulfil its mission, the Belgian Regulatory Body (constituted in Belgium by FANC and Bel V) has set up its own Research & Development programme, independent from the Waste Management Organisation's one. The Regulatory Body's Research & Development programme is mostly intended to investigate safety issues with the objective to be able to assess if the safety concept developed by the Waste Management Organisation fulfils the defined safety requirements. It includes the development and the follow-up of *in situ* experiments in underground research laboratories (e.g. in the Mont Terri project in Switzerland and at Tournemire in France). Such activities are essential to maintain and improve the scientific and technical skills, to strengthen the independence from the Waste Management Organisation and to build public confidence in the regulatory function.

More generally, Research & Development in underground research laboratories is important to the Regulatory Body as it allows investigating processes, technologies and activities important to safety under *in situ* conditions. In particular, it is essential to accurately identify and characterize the processes upon which the safety functions of a disposal system rely, as well as processes that may affect the system performance. It is also necessary to demonstrate that construction and operational methods and technologies are technically feasible and can be implemented as assumed in the safety case. Such research and development activities are of great importance to properly manage some of the key uncertainties associated with a disposal programme and in particular to identify, characterize and reduce them where needed.

The Belgian Regulatory Body's responsibilities

As the Belgian Nuclear Safety Authority, the mission of FANC (Federal Agency for Nuclear Control) is to ensure that people and the environment are protected against the hazards of ionizing radiations including the hazards related to radioactive waste. FANC carries out this mission in close collaboration with its technical support organization Bel V. FANC and Bel V together form the Belgian Regulatory Body.

In the context of radioactive waste management, this mission implies notably issuing advices on proposals for national waste management policies, the establishment of safety requirements, the safety oversight of the waste management activities performed by nuclear operators and by the Belgian Waste Management Organisation ONDRAF/NIRAS.

Regarding high-level and/or long-lived radioactive waste (category B & C waste), the first step in the decision-making process consists of determining a long-term management option meeting the safety objective without imposing undue burden on future generations. In the event that Belgium opts for geological disposal, the mission of the Belgian Regulatory Body will consist in verifying that the disposal facility is developed, built, operated and closed in a safe manner. This mission involves the review of the safety case and of its updates throughout the whole process of developing, licensing and implementing the geological disposal.

To perform adequate safety case reviews, the Regulatory Body needs technical expertise and support to:

- check the adequacy, completeness and justification of technical requirements and guidance;
- take informed decisions with full knowledge of the facts;
- justify advices and decisions;
- develop the capacities to understand and assess the safety case;

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- assess the adequacy, with regards to the regulatory framework, of the approaches followed to reach the safety objective and of their implementation.

The overall goal of regulatory reviews is to verify that the disposal facility will not cause an unacceptable adverse impact on human health or on the environment, both now and in the future (IAEA 2012; SITEX-II 2018). These reviews are carried out on the basis of a safety case submitted by the implementer.

Being an independent regulatory body and building the required expertise

The Belgian Regulatory Body has to be very careful to maintain its independence by not contributing to the development of the concept and design of the facility. In this regard, the Regulatory Body should define and implement from the beginning of the disposal project an appropriate organization to ensure allocation of sufficient resources.

In particular, the Regulatory Body has to identify its own research and development needs to build the required expertise in due time. This is essential as it allows maintaining and improving its scientific and technical skills, and thus contributes to its independence from the Waste Management Organisation and helps to build public confidence in the regulatory system (SITEX-II 2018).

It should be kept in mind that a multidisciplinary approach is very often needed to deal with interactions between the different fields of expertise and the coupling between various processes governing the evolution of geological disposals. Such a multidisciplinary approach can be implemented in different ways and typically calls for the collaboration of both generalists and specialists.

The Regulatory Body's Research and Development programme

Given the complex nature of geological disposal of radioactive waste and the need for the Regulatory Body to build up its own expertise, FANC and Bel V conduct an independent Research and Development programme (called Strategic Research Needs – SRN). It is important to highlight that the objectives of the Regulatory Body's Research & Development programme differ from those set up by waste management organizations. For instance, the Regulatory Body's Research & Development programme is mostly intended to investigate safety issues with the objective to be able to assess if the safety concept developed by the Waste Management Organisation fulfils the defined safety requirements. Special attention will be given to the identification of possible inadequate choices, assumptions, knowledge gaps, incompleteness, inconsistencies and mistakes (of reasoning or of implementation) in the safety assessment submitted by the Waste Management Organisation. These activities are therefore more 'a complement to' and 'a verification of' than a 'duplication of' the R&D activities performed by the Waste Management Organisation (SITEX 2014).

As such, the SRN constitutes, for the current and future years, the framework for developing and maintaining the Regulatory Body's expertise and tools necessary for the independent examination of the files relating to geological disposal. The SRN is also a support for transparent communication on Regulatory Body's activities and on the positions taken. The SRN will evolve throughout the life cycle of the waste management programme according to the evolution of the decision-making process and scientific understanding of phenomena important to safety. The focus is currently on safety issues relating to:

- the selection of the host geological formation and its surrounding environment;
- the disposal of waste in deep boreholes as a possible option for certain types of waste;
- operational and long-term safety aspects that may influence the design of a disposal facility.

The SRN is structured according to five key themes (see Fig. 1):

- **characterization of the components important for safety** to strengthen the knowledge on the characteristics and parameters important for safety (e.g. relating to radionuclide migration), including associated uncertainties related to the waste, the engineered components, the potential host geological formations available in Belgium and their surrounding environment (in particular the hydrogeology and the biosphere).
- **phenomena underlying safety** to strengthen the understanding of phenomena governing the migration of radionuclides and on which the ONDRAF/NIRAS' safety concept relies.
- **long-term stability** to strengthen the understanding of phenomena that could jeopardise the long-term safety of the geological disposal system for example, by altering the integrity of the engineered barriers. This includes disturbances induced by internal processes (for example those induced by excavation, operation, waste, the engineered components or the geological formation) or external to the system (for example glaciations, marine transgressions, seismicity or human activities).
- **design and technical feasibility** to strengthen the knowledge related to the design and the technical feasibility of building a geological disposal facility.

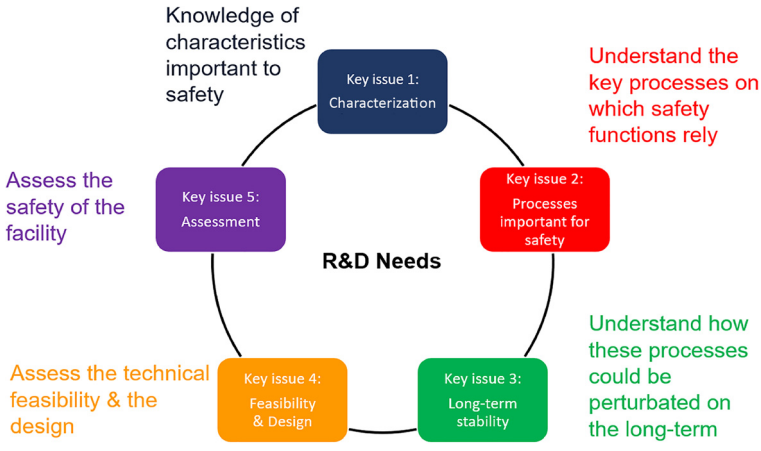

Fig. 1. The five key issues of the Regulatory Body's Research and Development programme SRN.

- **safety assessment** to assess the various long-term management options and to strengthen the knowledge in safety assessment and uncertainty management methods.

At the European level, organizations providing a technical and scientific support to regulatory decisions have developed a Strategic Research Agenda (SRA) (SITEX-II 2016). The Belgian SRN served as an input for its development. This SRA was one of the key inputs for the development of the SRA of the European Joint Programme on Radioactive Waste Management (EURAD). Several technical support organizations are involved in the first implementation phase of EURAD (2019–24), which addresses several topics of its SRA.

Underground research laboratories as an important support to the management of uncertainties

Decisions associated with a geological programme are made in the presence of irreducible and reducible uncertainties. The management of both types of uncertainties is a key issue (Lemy and Bernier 2013). Typically expected components of an uncertainty management strategy include (Bernier and Lemy 2013):

- the identification of the uncertainties;
- their characterization;
- the analysis of their potential relevance for safety;
- their treatment in the safety assessment;
- the assessment of the need and possibility to avoid, reduce or mitigate uncertainties.

The analysis of safety relevance can lead to the exclusion of the uncertainty from further consideration, e.g. it can be demonstrated that the uncertainty on a particular parameter is not important to safety; the event/process can be shown to have a very low probability of occurrence. If not, the uncertainty may need to be 'treated' in the safety assessment by addressing the uncertainty explicitly, by bounding the uncertainty, or by using an agreed stylised approach to avoid addressing the uncertainty explicitly.

The management of uncertainties is an iterative process whereby R&D plays an important role. *In situ* experiments in underground research laboratories (URLs) allow decreasing (potentially) safety-relevant uncertainties by conducting tests at scales and under conditions that are representative of those that will prevail in a real repository. URLs also allow us to demonstrate the feasibility of construction and waste emplacement techniques.

Typically URL *in situ* experiments aim to decrease uncertainties on the:

- host-rock characterization including its initial state and conditions;
- understanding of hydro-mechanical processes and more specifically the Excavation Damaged Zone extent around disposal galleries and its evolution;
- radionuclide transport processes;
- influence of the temperature on the hydro-mechanical–chemical evolution of the disposal system and transport properties;
- hydration processes of engineered materials and associated time-scales;
- effective characteristics and therefore performance of installed components;
- degradation processes (corrosion, alkaline front, etc.).

However, such experiments lead sometimes to 'new' uncertainties and processes that were not identified before.

URLs, an important support to the Regulatory Body's Research and Development programme

URLs constitute very broad R&D platforms gathering many participating countries and organizations. The participation in the R&D programmes of URLs is essential to develop a broad, coherent and independent Regulatory Body's vision. The participation in URL consortia greatly facilitates the follow-up of the state-of-the-art practices in the fields of scientific and technical expertise required for a Regulatory Body. Additionally, the direct access to information and the exchanges with internationally recognized experts allow us to save a significant amount of time and to increase the efficiency and credibility of the Regulatory Body.

The Belgian Regulatory Body is involved in the research and development programmes of the Mont Terri URL in Switzerland and in the Tournemire URL in France. This participation allows strengthening its knowledge in the areas associated with the SRN's priorities. The scientific and technical survey of results of other URLs, like HADES in Belgium or Bure in France, also constitutes an important source of knowledge. The investigation of processes observed for different host rocks and engineered components allows a better understanding of the phenomena at play and the relative importance of the associated parameters. It contributes to the validation of the models obtained by comparing modelling results with experimental results. The highlighting of similar processes observed in different laboratories is also of particular importance. Despite the differences in the host rocks investigated in URLs, some observed characteristics and processes present similarities. Taking note that different research teams, working independently and using different instrumentation devices, are able to point out similar evidences is a way to build confidence in the current understanding of geological disposal systems and to manage uncertainties.

Participation in the Mont Terri URL

FANC is a member of the Mont Terri consortium (https://www.mont-terri.ch/) and is involved in a wide range of experiments covering areas such as geomechanics, geophysics, hydrogeology, geochemistry, microbiology and transport (radionuclides and gas) experiments, i.e.

- FE-M: Long-term monitoring of the full-scale emplacement experiment;
- HA-A: Variability of hydrogeological and geophysical parameters of Opalinus Clay experiments;
- BN: Bitumen–nitrate clay interaction;
- CI : Cement–Opalinus Clay interaction;
- CS-C: Shale properties for geological CO_2 storage
- GD: Geochemical data;
- MA: Microbial activity;
- DR-B: Long-term diffusion;
- HT: Hydrogen transfer.

FANC is also principal investigator of the DR-C (diffusion under thermal gradient) experiment. The objective of the experiment is to study the possible impact of a thermal gradient on the diffusion of different radioactive tracers in Opalinus Clay. In current safety assessment of geological disposal, the impact of thermal gradients generated by the radioactive high-level waste on the diffusion of radionuclides through the host rock is usually disregarded because the full containment of radionuclides in the waste canister is assumed during the entire thermal phase. However, in case of premature failure of the containment canister during the thermal phase, the radionuclides released in the pore water could migrate at higher diffusion rates. It is therefore essential to estimate the possible increase in diffusion rates to better assess the possible contamination of the near-field in the event that the canister needs to be retrieved. Depending on the concept other transport processes than diffusion may have to be taken into account.

While experiments have been carried out in surface laboratories (Van Loon *et al.* 2005; Sánchez *et al.* 2008), there is a lack of experimental data regarding the effect of temperature on radionuclide diffusion under *in situ* conditions. For this reason, this scenario should be better studied to increase confidence in the long-term safety of geological disposal for heat-emitting radioactive waste. Indeed, this scenario is especially important if retrievability of the waste is considered and in view of the implementation of the defence in depth principle, which is a key safety requirement. The study of scenarios whereby the failure of a safety function or component is assumed, like the one investigated through this experiment, can also be important for gaining public confidence in geological disposal.

Figure 2 shows the design of the DR-C experiment developed by SOLEXPERTS (Fierz *et al.* 2020). The DR-C experiment is being installed in the sandy facies, for which there is a lack of diffusion data. A duplicate experiment at ambient temperature, here referred to as a 'reference experiment' is carried out to provide *in situ* reference diffusion data. The first scoping calculations (Pochet 2020) suggested that a distance of at least 10 m should be maintained between the heated and the reference experiment in order to prevent thermal effects on the reference experiment. DR-C is being installed in the Passwang Niche (heated experiment – BDR-C1) and in Gallery 18 (reference experiment – BDR-C2) where this

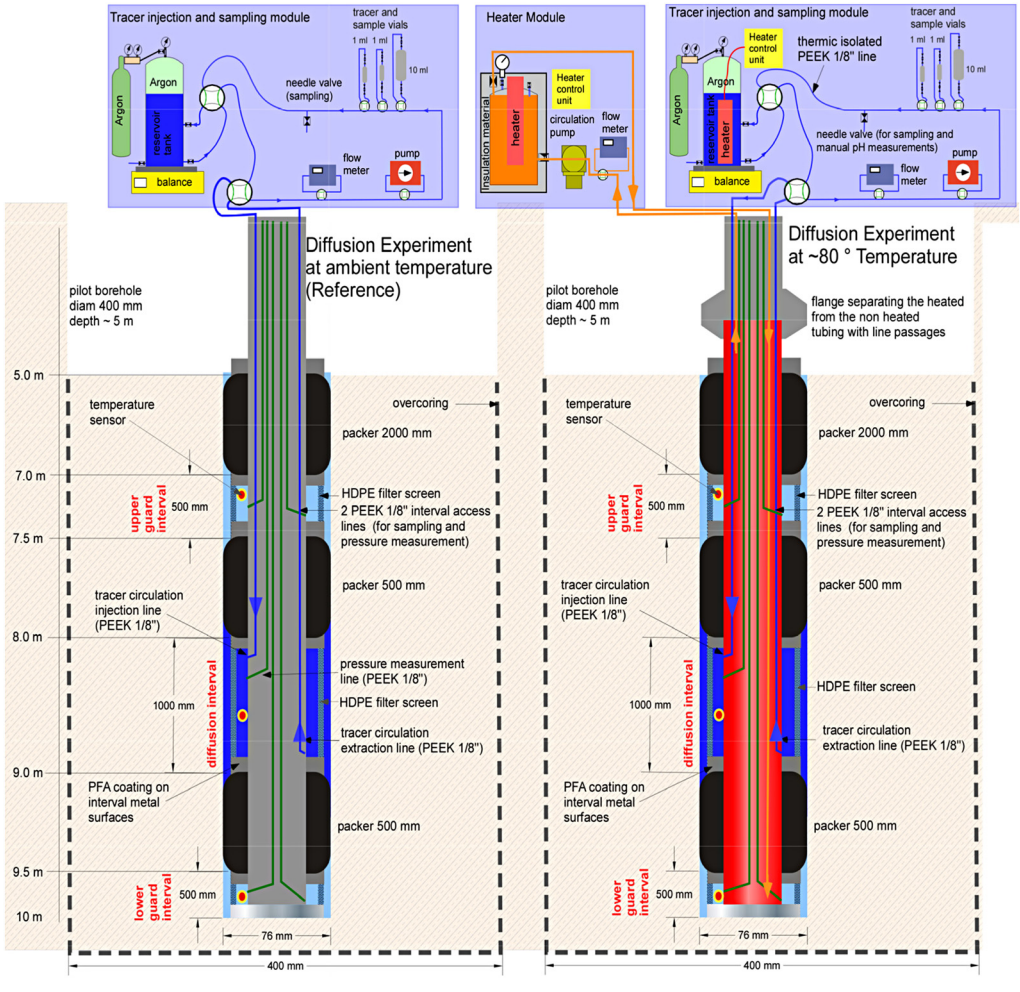

Fig. 2. Experimental setup showing the heated (BDR-C1; right) and reference (BDR-C2; left) diffusion experiments performed at Mont Terri in the framework of the DR-C experiment (Fierz *et al.* 2020).

criterion is fulfilled (see Fig. 3). The ambient temperature and heated experiments consist both of a 5 m long pilot borehole with a diameter of 400 mm in which a central borehole with a diameter of 76 mm is drilled. The central borehole of the heated experiment is drilled perpendicularly to the niche axis and is heated by a hot water circulation loop. The heater module is designed to reach a temperature of 80°C at the interface of the central borehole with the Opalinus Clay along the diffusion interval. The heater module and its flow lines are thermally insulated in order to prevent heat losses. In both diffusion boreholes, a tracer injection and sampling module circulates a cocktail of radioactive tracers, which diffuse into the Opalinus Clay through a HDPE (High Density Polyethylene) filter screen. Upper and lower intervals also equipped with HDPE filters screens are available for water sampling. The intervals are separated from each other by inflatable packers.

Three observation borehole(s) are drilled around the central heated borehole and equipped with the proper instrumentation to monitor relevant Thermo-Hydro-Mechanical processes. Two observation boreholes (BDR-C4 and BDR-C5) are equipped with fibre optic sensors (FBG – Fibre Bragg Gratings) for the monitoring of temperature and strain while a 3-packer system will be installed in the third observation (BDR-C3) borehole for the porewater pressure monitoring. Figure 4 shows the arrangement of the three observation boreholes relative to the heated experiment borehole.

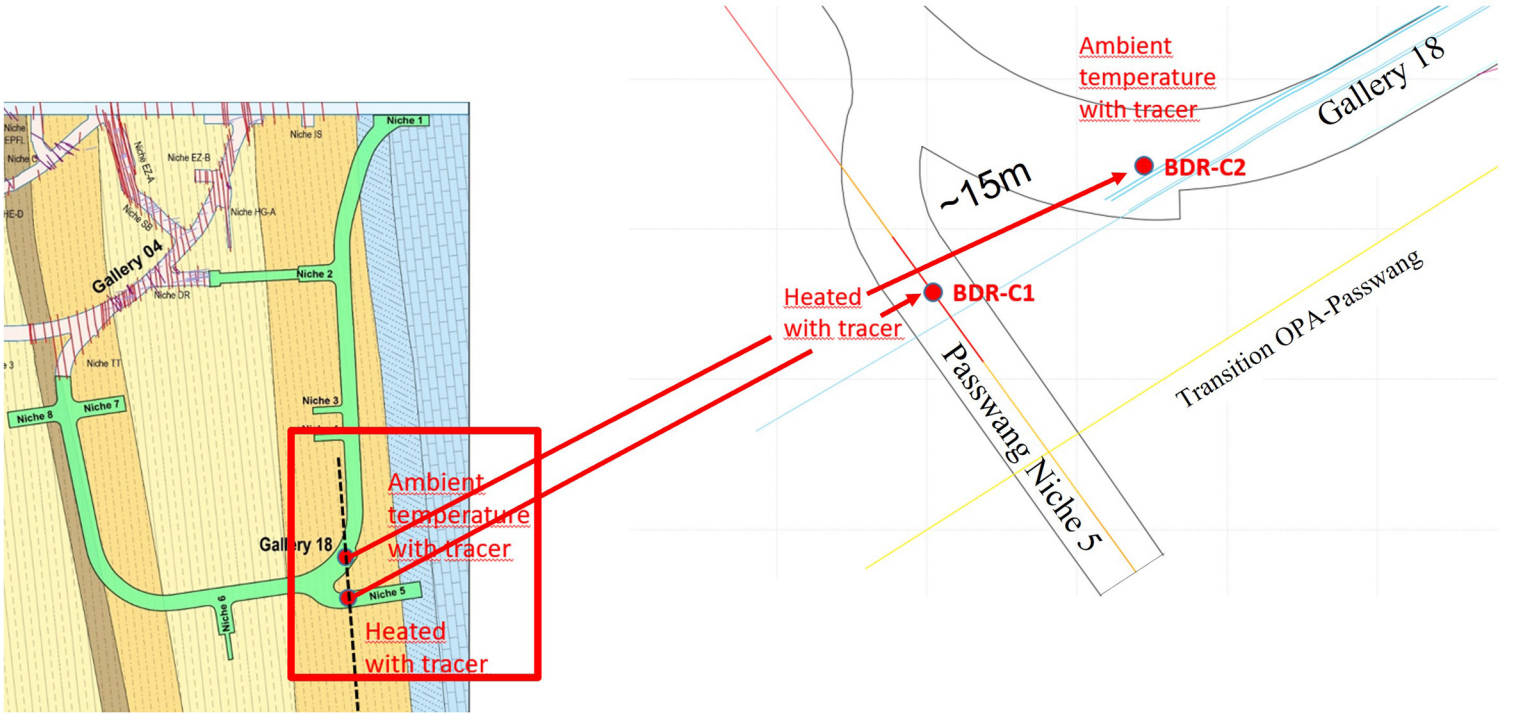

Fig. 3. Location of the DR-C experiment installed in the sandy facies of Opalinus Clay (OPA) at the Mont Terri underground rock laboratory. BDR-C1 (heated experiment) and BDR-C2 (reference experiment) are installed in Passwang Niche 5 and Gallery 18, respectively, along the same bedding plane (black dashed line).

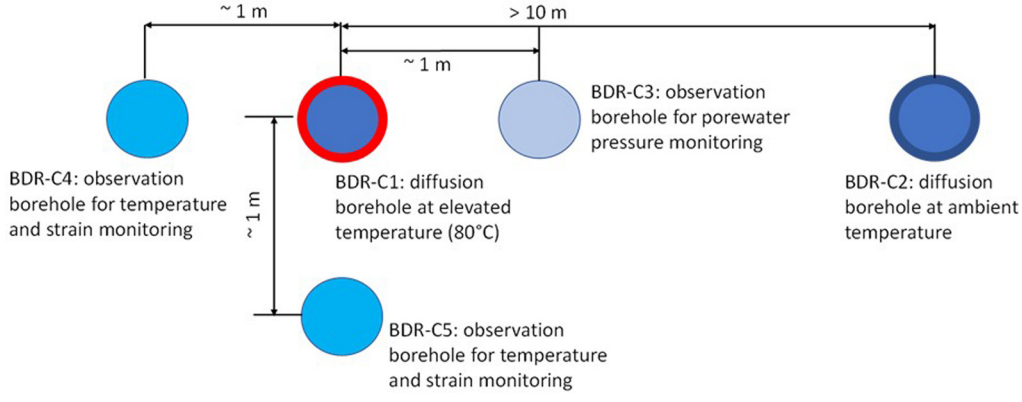

Fig. 4. Reference experiment (BDR-C2) and arrangement of the monitored boreholes (BDR-C3–C5) around the heated experiment (BDR-C1).

It is planned to use the following tracer cocktail: HTO, $^{125}I^{-}$, $^{129}I^{-}$, $^{60}Co^{2+}$, $^{137}Cs^{+}$, $^{22}Na^{+}$. According to the results of the first scoping calculations, the heating time to reach 80°C at the interface with the Opalinus Clay and to establish a quasi-stable temperature gradient near the heated experiment borehole should be of the order of one year. At the end of the diffusion experiments, the boreholes will be over-cored within a diameter of 400 mm. The results of the first scoping calculations (see Fig. 5) show that this distance should be reached by a non-sorbing diffusing tracer in less than 1 year in the cases of the heated as well as ambient experiments.

Participation in the Tournemire URL

Both FANC and Bel V are involved in activities of the Tournemire URL (https://www.irsn.fr/EN/Research/Scientific-tools/experimental-facilities-means/Tournemire/Pages/TOURNEMIRE-experimental-station.aspx).

FANC was mainly involved in the SEALEX research project (Barnichon *et al.* 2011) dedicated to assessing the effectiveness and robustness of seals in terms of long-term hydraulic performance. FANC supported also PhDs, initiated by IRSN related to the SEALEX experiments, studying the hydration process of bentonite materials and the influence of potential salinity and alkaline fronts (e.g. Molinero-Guerra *et al.* 2020).

FANC is now developing together with IRSN an *in situ* experiment having similar objectives than the DR-C experiment installed at Mont Terri in order to study the influence of temperature gradients on the transport of radionuclides. The main difference with the DR-C experiment at Mont Terri concerns the scale of the experiment (1 m diameter), which allows for a larger injection area.

Bel V has co-funded several PhDs investigating possible perturbations between several engineered barriers in the near-field of a disposal facility and how they could affect the sorption of radionuclides.

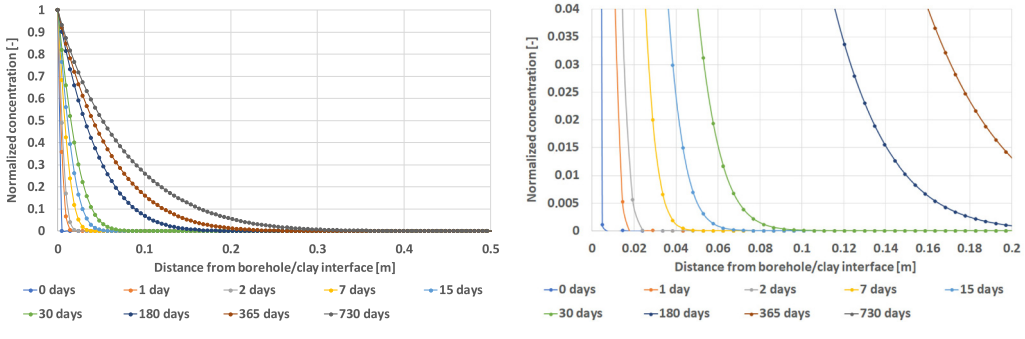

Fig. 5. Normalized tracer (NaI) concentration profile in the porewater of the Opalinus Clay in function of the radial distance from the borehole/clay interface at mid-height of the diffusion interval ($z = -8.5$ m) and for various times after tracer injection (scoping calculations).

Several PhDs were co-funded with notably IRSN (e.g. Fatnassi 2015; Lalan 2016; Seigneur 2016; Rajyaguru 2018) and were based on experiments conducted in the Tournemire URL. Moreover, since 2019, Bel V is involved in the BACUCE experiment carried out in Tournemire in the framework of the EURAD ACED Work Package ('Assessment of chemical evolution of HLW and ILW disposal cells'). BACUCE focuses on the understanding of the evolution of steel/concrete interfaces during the thermal phase of a disposal facility, as well as on the impact of possible heterogeneities (e.g. voids at the interface) on this evolution. Three BACUCE experiments were designed in collaboration with IRSN, Subatech, Ecole des Mines and ZAG and installed in September 2020. First results are expected in the next few years.

Conclusions

In the context of geological disposal, the mission of the Belgian Regulatory Body (constituted in Belgium by FANC and Bel V) is to verify that the repository is developed, constructed, operated and closed in a safe manner, i.e. that people and the environment are protected against the hazards of ionizing radiation due to the radioactive waste, without imposing undue burdens on future generations. This covers several types of activities such as the establishment of regulatory requirements, as well as of procedures and conditions for meeting these requirements at the various stages of the licensing process.

To fulfil this mission, it is therefore important that the Regulatory Body conducts its own independent Research and Development programme dedicated to the understanding of the disposal system and the assessment of processes that can potentially influence radionuclide transport in the disposal system and in its surrounding environment. The Belgian Regulatory Body's Research and Development programme includes *in situ* experiments supporting the identification and characterization of uncertainties regarding the evolution of the system and the development of an appropriate set of scenarios for the assessment of long-term safety. This is essential to investigate whether an appropriate level of protection will be provided by the proposed disposal system considering various conceivable evolutions of this system. An important issue is for example the influence of a thermal gradient on the engineered barriers and the transport of radionuclides that can be best studied through *in situ* experiments in URLs. Indeed, the use of *in situ* experiments makes it possible to avoid uncertainties linked to the transposition of the results of tests carried out in traditional laboratories to actually expected conditions. The participation in URL experiments provides also a unique opportunity for the Regulatory Body to identify experimental challenges possibly faced by the Waste Management Organisation and to collaborate with internationally recognized experts in various disciplines relevant to the safety case.

The R&D objectives set by the Regulatory Body differ from those set by the Waste Management Organisation. The Regulatory Body will mostly investigate issues directly related to safety with the objective to verify the adequacy of the approaches followed by the Waste Management Organisation to reach the safety objectives.

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Author contributions **FJB**: writing – original draft (lead); **VD**: writing – original draft (equal); **FL**: writing – original draft (equal); **GMP**: software (lead), writing – original draft (equal); **MS**: writing – review & editing (supporting); **GV**: writing – review & editing (supporting); **CM**: writing – review & editing (supporting).

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Data availability All data generated or analysed during this study are included in this published article.

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