Important roles of underground research laboratories for the geological disposal of radioactive wastes: an international perspective

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Abstract: After decades of research, development and demonstration (RD&D), mature concepts for the geological disposal of long-lived and high-level radioactive waste exist and some are close to being implemented. Underground research laboratories (URLs) have made an essential contribution to this progress. They enable *in situ* characterization and testing of host rocks and the demonstration of technologies and component performances at representative scales and under realistic geological conditions. They also offer a tool for training personnel and show aspects of the geological disposal concepts to stakeholders, including the public. In this paper we will present the different types and roles of URLs and we will discuss how the RD&D role of URLs has evolved and how it is likely to evolve in the near future.

For several decades, waste management organizations and research institutes worldwide have been developing concepts for the geological disposal of long-lived and high-level radioactive waste. Today, scientifically and technically mature geological disposal concepts exist and some countries have implemented or are progressing towards implementing these concepts.

Underground research laboratories (URLs) have played an essential role in this progress. They provide access to the geological environments considered for geological disposal. This allows characterization of the host rock *in situ*, the performance of tests under realistic geological conditions and demonstration of the feasibility of constructing, operating and closing underground repositories (IAEA 2001; NEA 2013). As such, they have contributed to an enhanced understanding of the key processes affecting post-closure safety and to building confidence that geological disposal facilities can provide a safe disposal solution for long-lived and high-level radioactive wastes.

Types of URLs

Broadly speaking, two main types of URLs can be distinguished: generic ones and site-specific ones (NEA 2013). Generic URLs are constructed at sites that are not planned to be used as the disposal site. They are typically constructed at locations with geological conditions representative of the disposal concept under consideration. They can contribute to testing and demonstrating excavation techniques and gaining understanding of the host rocks in which they are excavated.

In Switzerland, two generic URLs are in operation: the Mont Terri Rock Laboratory in argillaceous rocks and the Grimsel Test Site in crystalline rocks (Fig. 1). Both sites are not considered as potential disposal sites, but they do offer the possibility to gain understanding about these host rock types and run experiments at representative scales and under realistic geological conditions.

Site-specific URLs are implemented at or near a potential disposal site. Compared with generic URLs, site-specific ones have the advantage that they operate in the actual conditions that will apply to the disposal facility. This can broaden the scope of research, development and demonstration (RD&D) that can be done in these facilities. Some restrictions may, however, apply because the URL activities must not jeopardize the safety of the future disposal facility.

The infrastructure of the site-specific URL can be shared by the eventual disposal facility. This can

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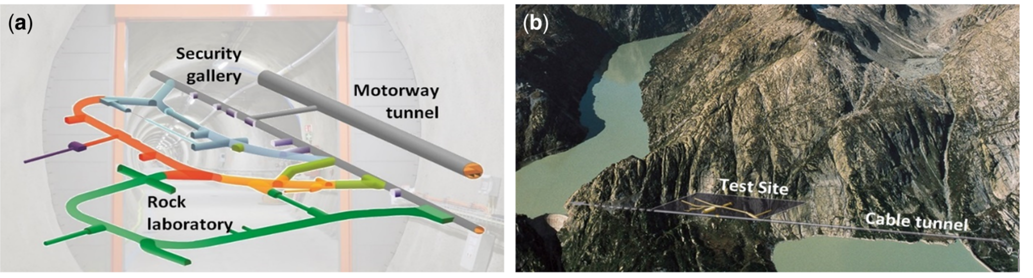

Fig. 1. (**a**) The Mont Terri Rock Laboratory and (**b**) the Grimsel Test Site are two generic underground research laboratories (URLs) that have been part of the Swiss research, development and demonstration programme for the geological disposal of radioactive waste. Source: (a) courtesy of Swisstopo; (b) courtesy of NAGRA.

include surface buildings, utilities (e.g. electricity, water and communication), security infrastructure, access roads to the site or access shafts to the underground facility. This is the case for the WIPP facility in New Mexico (USA), a geological disposal facility for long-lived transuranic (intermediate level) radioactive waste (Fig. 2). The site, underlain by a bedded salt layer, was first chosen for further research in the mid-1970s. In 1981 the construction of the facility started and between 1984 and 1990 several large-scale underground experiments were performed (heated tests were performed for the benefit of a different salt site for heat-generating defence waste, while some plugging and sealing tests were performed for the WIPP mission). WIPP has been disposing of transuranic waste since 1999. More recently, a new phase of underground research is underway at WIPP.

Site-specific URLs are sometimes intended as a sort of ‘performance confirmation facility’. This facility is then monitored for several years to verify that its performance complies with what is assumed in the safety case, which is the collection of arguments and evidence demonstrating the safety of the facility. The ONKALO® underground rock characterization facility (URCF) in Finland is an example of such a facility. It is part of the licensed Olkiluoto geological disposal facility (GDF) (Fig. 3). The ONKALO® URCF is excavated in crystalline rock and will become part of the access infrastructure to the Olkiluoto GDF. ONKALO® has been used to characterize the host rock, develop rock construction and rock suitability classification methods, and run several *in situ* experiments. A test area has been constructed for a ‘trial run of final disposal’ in 2023–24 to test the technology, organization and procedures that will be used during the disposal operations.

Underground research laboratories may be purpose built or may use existing underground facilities, like a tunnel or an abandoned mine. Making use of existing facilities can reduce the overall costs of the URL programme and can benefit from already available geological data and operating experience. The Mont Terri Rock Laboratory uses an existing security gallery of a motorway tunnel as its access route. In the Tournemire URL (France) an old railway tunnel excavated in a clay formation was converted into a URL (Fig. 4). Several other URLs have used mines, such as Project Salt Vault (USA),

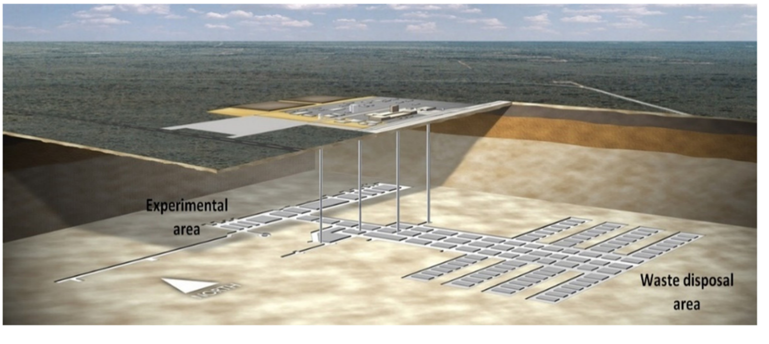

Fig. 2. The WIPP facility was first a URL but was later extended to become a waste disposal facility for long-lived intermediate-level waste. Source: courtesy of the US Department of Environment.

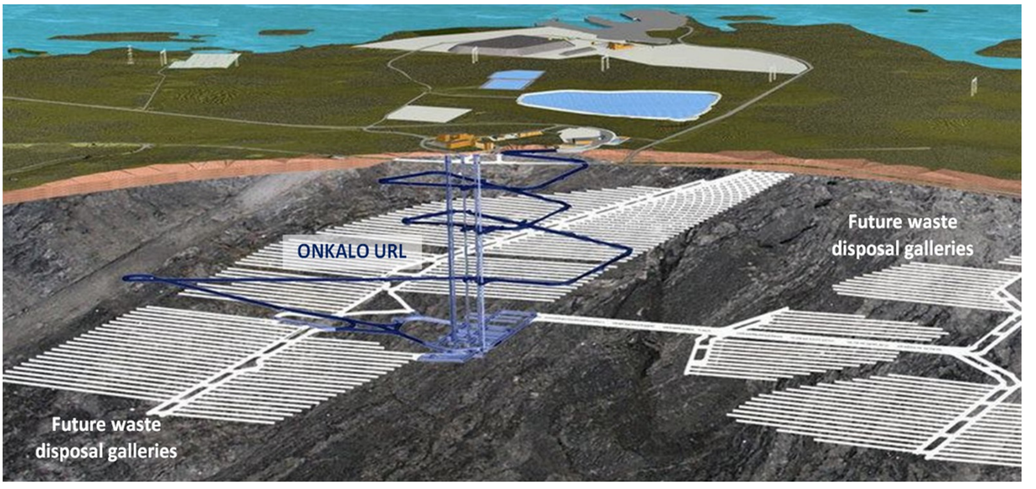

Fig. 3. The ONKALO® underground rock characterization facility (URCF) is a part of the access infrastructure to the current research facility and future disposal galleries. Source: POSIVA.

Stripa (Sweden), Kolar (India), Tono and Kamaishi mines (Japan), Asse (Germany) and the Josef Underground Research Centre (Czech Republic).

Existing underground facilities have the disadvantage that the site is already disturbed. This makes it difficult or even impossible to establish the original baseline conditions. Converting existing underground infrastructure into a URL is therefore mainly used for generic URLs. There are, however, exceptions. The Konrad mine in Germany was used until the 1970s for mining iron ore (Fig. 5). After the iron mining stopped, RD&D was done in the mine to evaluate the possibility of using it for the disposal of low- and intermediate-level radioactive waste. Following on the positive outcomes of the research, a licence application was submitted to convert the mine into a disposal facility. In 2007, the licence was obtained and disposal operations are expected to start in 2027.

Figure 6 shows the locations and types of 33 URLs worldwide: 24 generic and nine site-specific URLs. Eighteen are in or attached to an existing underground facility while 15 are built at a site without developed underground infrastructure, such as an existing mine or tunnel. Sixteen are constructed in crystalline rocks, six in evaporites, five in

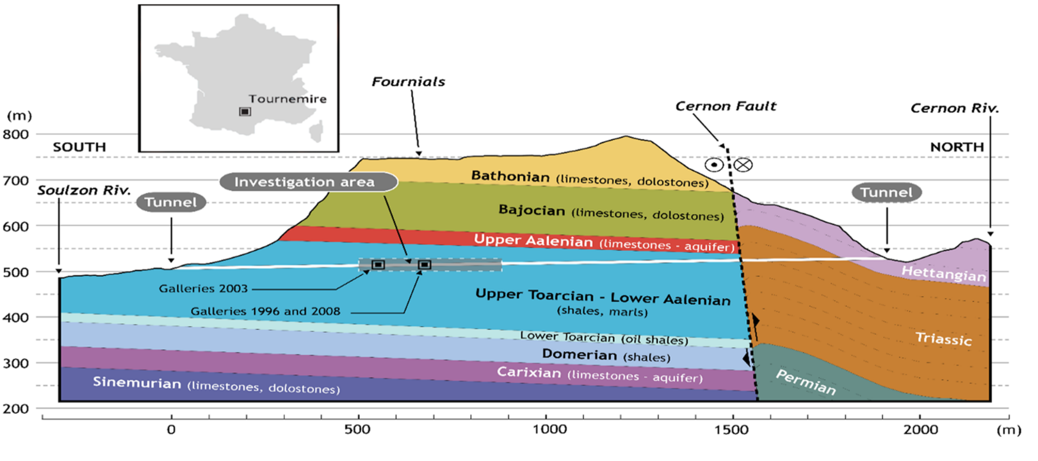

Fig. 4. The Tournemire URL uses an old railway tunnel excavated in clay. Source: modified from Matray *et al.* (2007), courtesy of IRSN.

Fig. 5. The Konrad repository is an extension of an old iron mine. Source: BGE.

argillaceous rocks and six in other rock types, like volcanic tuff or sedimentary rocks other than argillaceous rocks.

The roles of URLs

URLs have played an important role in developing the scientific and technical basis for the geological disposal of long-lived and high-level radioactive waste (Delay *et al.* 2014; Blechschmidt and Vomvoris 2017). Their role, however, stretches beyond a purely scientific and technical one. They offer a useful tool to train personnel and to inform stakeholders about geological disposal.

The primary duties performed at a URL include:

(1) *in situ* characterization;
(2) performance testing;
(3) technology development, demonstration and optimization;
(4) creating organizational readiness for the geological disposal project;
(5) training and professional development;
(6) stakeholder involvement; and
(7) international collaboration.

URL activities often serve several of these purposes. For example, an experiment to test the *in situ* behaviour of bentonite will aim to expand the scientific knowledge on bentonite and sealing systems.

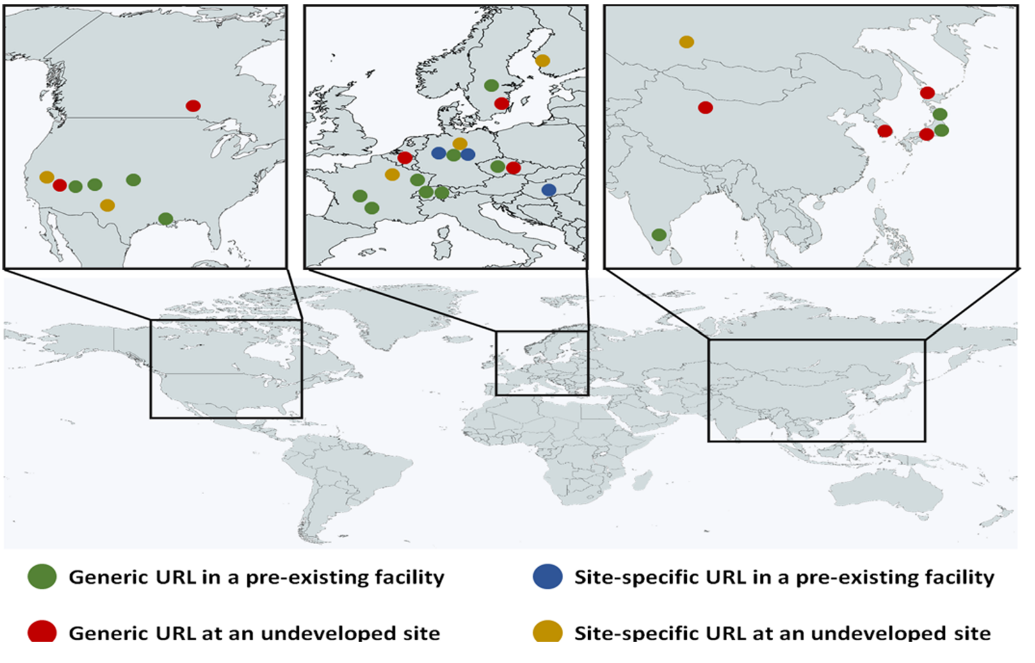

Fig. 6. Locations and types of 33 URLs worldwide. Source: courtesy of the International Atomic Energy Agency.

However, the experiment installation itself can demonstrate that the sealing systems can be built. It can be used to train personnel and show the public how repositories can be sealed. Furthermore, different international partners may benefit from collaborating on the experiment.

Waste management organizations and research institutes are not the only parties involved in URL activities. Regulatory authorities can also engage in URL RD&D to build their capabilities. The Tournemire URL is operated by IRSN, the French national public expert in nuclear and radiological risks. The Belgian, French, German and Swiss nuclear regulators (FANC, IRSN, BASE and ENSI) are partners in the activities done in the Mont Terri Rock Laboratory, as well as research organizations like ETH Zürich, PSI and the Helmholtz Centre.

In situ *site characterization*

Characterizing a geological environment that is several hundred metres deep can to some extent be done by drilling boreholes from the surface. Core samples can be obtained and tested in the laboratory and geophysical tools can be run down the borehole. However, these methods have their limitations. They only provide data over a relatively small scale and some laboratory measurements, such as porosity and diffusivity, are known to be subject to error owing to sample disturbance effects.

URLs have allowed detailed measurements of the thermo-hydromechanical, chemical and biological characteristics of the geological environment at larger scales and with more accuracy. The data are derived at larger and more realistic scales compared with laboratory or borehole measurements (IAEA 2023). They can reveal heterogeneities that would be difficult to determine based on surface investigations. This can result in a better understanding of lithological variations and geological structures such as fractures or faults.

The focus of the geoscientific research differs depending on the specific properties of the different host rocks. POSIVA used a niche in the ONKALO® URCF to characterize deformation zones and hydraulically active features in the crystalline bedrock (Fig. 7). Rock volumes with these less favourable features will be avoided for the disposal of spent fuel canisters. POSIVA therefore developed a rock suitability classification system: a method to locate rock volumes suitable for disposal (POSIVA 2012). The site characterization work in the ONKALO® URCF has enabled the development and testing of this rock suitability classification system. POSIVA also investigated various properties of the host rock in ONKALO®, such as the retention and sorption of radionuclides, thermal conductivity, the excavation damaged zone, rock mechanical properties, groundwater flow and geochemical processes.

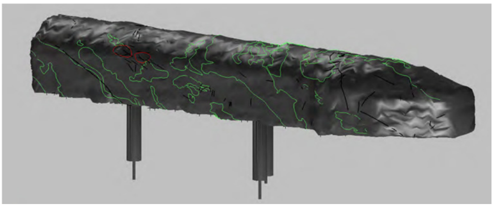

Fig. 7. Geological mapping data of fractures and lithological contacts in a niche in the ONKALO® URCF. Source: POSIVA.

The value of a site-specific URL for *in situ* characterization is obvious. However, *in situ* characterization in a generic URL can also be valuable. It can provide insight into the fundamental behaviour of host rock types and improve our ability to assess coupled processes. It can help to validate the numerical models used to predict this behaviour. To examine the coupled thermo-hydromechanical behaviour of Boom Clay at a representative scale, a large scale heater test, called the 'PRACLAY Heater Test', was set up in the HADES URL (Van Marcke *et al.* 2013; Fig. 8). The interface between a 30 m long gallery section and the clay will be heated for at least 10 years to a temperature of 80°C.

Finally, a particular aspect of *in situ* characterization is the characterization of the excavation disturbed zone (EDZ). Obviously, characterizing the excavation disturbed zone requires an excavation. Many URL experiments have been conducted to enhance our understanding of the EDZ. Underground research laboratory excavation has also allowed the optimization of excavation methods to minimize the EDZ. Experiments in the Whiteshell URL in Canada helped to improve the excavation geometries in a high-stress environment, which minimized the excavation damage in the crystalline rock (Chandler 2003).

Performance testing

The *in situ* characterization performed in a URL contributes to the scientific basis underpinning the geological disposal concept. However, the scientific and technical R&D done in a URL goes further than only characterizing the host rock. The URL provides the opportunity for large-scale testing of the performance of the host rock, waste canisters, backfill, seals and other components or materials under realistic geological conditions.

The corrosion rates of metals like stainless steel, carbon steel and copper have been measured in URLs. The Korea Atomic Energy Research Institute

Fig. 8. Installation of the heating system for the PRACLAY Heater Test in the HADES URL. Source: courtesy of ESV Euridice.

(KAERI) studied the corrosion of copper by conducting a long-term corrosion test in the KAERI Underground Research Tunnel (Fig. 9). Samples of these materials were placed in test chambers that were directly supplied with fresh underground water (KAERI 2016).

In Japan a full-scale engineered barrier system (EBS) was installed in the Horonobe URL to evaluate the EBS performance and technical feasibility (Fujita *et al.* 2014) (Fig. 9). The EBS consisted of a vertical deposition borehole drilled from a horizontal gallery. A carbon steel overpack was placed in the borehole and the void between the overpack and borehole wall was filled with pre-compacted bentonite blocks. The whole setup was extensively instrumented to monitor the EBS evolution.

These RD&D activities have identified the main processes or features relevant to the release and migration of radionuclides in the EBS and host rock. This enabled development of the models used for the long-term safety assessment of the GDF. Radionuclide migration experiments have been conducted in which radioactive tracers were injected into the host rock and their migration was monitored over the following years. An example is the ‘Colloid Formation and Migration’ project carried out at the Grimsel Test Site (Schäfer *et al.* 2009; Fig. 10). Radionuclides and colloids are injected into an

(**a**) (**b**)

Fig. 9. (**a**) Test chambers in the KAERI Underground Research Tunnel facility measuring the corrosion of copper and (**b**) placement of instrumentation in a buffer of pre-compacted bentonite blocks as part of the engineered barrier system test in the Horonobe URL. Source: (a) courtesy of KAERI and (b) courtesy of JAEA.

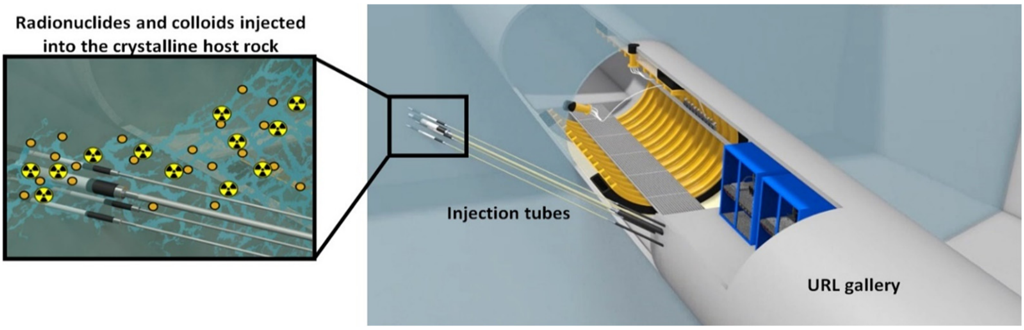

Fig. 10. The Colloid Formation and Migration project at the Grimsel Test Site, setup for the long-term *in situ* experiment. Source: courtesy of NAGRA.

advective flow in the host rock and their flow is monitored.

Technology development, demonstration and optimization

The URLs have offered the opportunity to develop, test, demonstrate and optimize the technologies needed for geological disposal, such as shaft and underground gallery construction, waste handling and emplacement, backfilling and sealing operations. The construction history of the HADES URL is an excellent example illustrating how the URL allowed the development and optimization of the technology to construct shafts and galleries in a plastic clay formation (Bastiaens and Bernier 2006).

The equipment and methods to emplace canisters and compacted bentonite blocks were tested in the Äspö Hard Rock Laboratory (SKB 2015) (Fig. 11). This also allowed SKB to develop and test quality assurance procedures for these operations.

In the ONKALO® URCF, the demonstration of prototype disposal concepts is planned as part of the GDF programme at Olkiluoto. It is likely that similar prototype demonstrators will be performed in other URLs as part of the GDF programme. However, as the HADES and Äspö URLs demonstrate, these types of experiments do not necessarily need to be done in site-specific URLs. The knowledge about the technologies developed and tested in generic URLs can sometimes be transferred to other sites with similar geologies.

The underground experiments require the use of a wide variety of instruments. This means that a lot of expertise has been gained over the years in instrumenting components of the geological disposal concept (Mayer *et al.* 2012). This expertise will support the development of monitoring plans for geological disposal.

Creating organizational readiness for the geological disposal project

Another benefit of constructing and operating a URL is gaining experience in certain aspects of planning and realizing a GDF project. Like a GDF, a URL

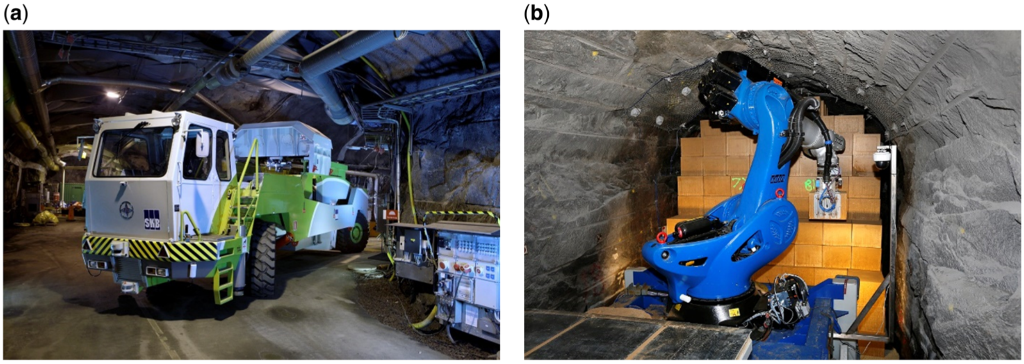

Fig. 11. (**a**) Tests in the Äspö Hard Rock Laboratory to demonstrate the deposition of a dummy canister and (**b**) the installation of bentonite backfill blocks. Source: courtesy of SKB.

needs to be sited. This can require a site selection process, site characterization, stakeholder involvement and adherence to applicable legal and regulatory requirements. Once a site is selected, the necessary permits and licences need to be obtained.

China has started constructing a URL in crystalline rocks (Wang *et al.* 2018). The URL is located in the NW of the country, in the Beishan area (Fig. 12). The site selection process started in 1985 with a nationwide screening and the selection of the ultimate site is the outcome of 33 years of investigations. The URL site itself was characterized extensively using geological mapping, geophysical surveys, borehole drilling, hydraulic testing and *in situ* stress determinations.

Underground research laboratory programmes also extend over decades and they require solid project management. Human resources need to be managed to guarantee organizational continuity and knowledge management, which are crucial to preserve records and knowledge over the timespan during which URLs are operational. The management expertise gained from operating a URL will be come in handy when embarking on a geological disposal project.

The same applies to ensuring operational safety. Underground research laboratories need to be operated in a safe way. Safety risks are related to working in an underground and confined environment, the use of heavy machinery and loads, and fire and dust hazards. Based on the recommendations of a fire safety study conducted in the HADES URL in 2016, two fireproof doors were installed in the facility in 2020. Such regular evaluations and continuous improvements of the safety infrastructure are essential to develop a safety culture within the whole organization operating the URL. Such a safety culture will also be needed for the geological disposal project. The URL therefore offers an excellent tool to pro-actively develop and promote this culture in advance.

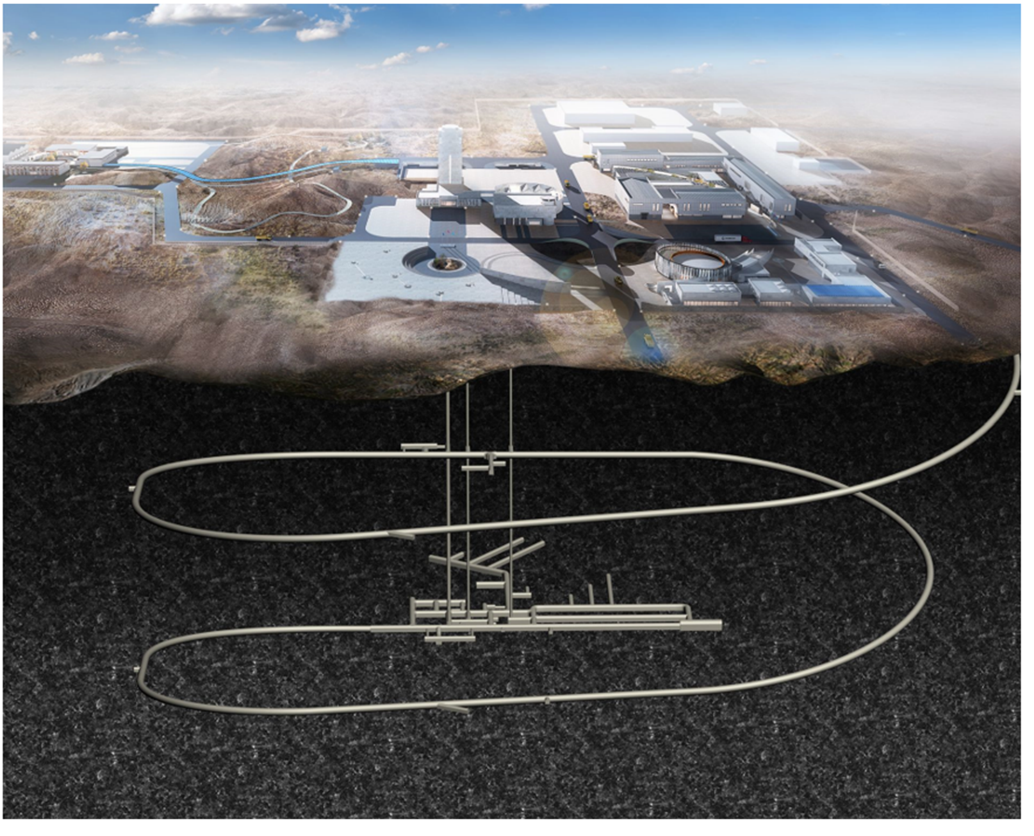

Fig. 12. Preliminary design of the Beishan URL with one access ramp, three shafts and experimental tunnels. Source: courtesy of BRIUG.

Training and professional development

Apart from training staff in project management and instilling a safety culture, URLs can provide opportunities for the professional development of scientists and engineers. The scientific and technical basis for geological disposal requires a broad and unique set of skills and expertise. Underground research laboratories can assist in attracting the right professionals and offer them an environment where they can familiarize themselves with the science and technology that will come into play in a GDF programme.

In 2007 the Czech Technical University in Prague converted a tunnel in an abandoned gold mine into the ‘Josef Underground Research Centre’ (Fig. 13). The main purpose of the research centre is to teach students in the fields of geotechnics and geology (Vasicek and Svoboda 2009). It gives student the opportunity to take measurements and conduct experiment in an *in situ* environment. Students are also encouraged to participate in the various research projects that are ongoing in the Josef URL. The URL increases the attractiveness of the geotechnical and geological courses offered by Czech Technical University and it provides students with practical experience.

Stakeholder involvement

A geological disposal project is not only a scientific or technological endeavour. Perhaps the biggest challenge is gaining political and social acceptance for the project (IAEA 2022). It is therefore essential for the success of the project that stakeholders are involved. Underground research laboratories can play a major role in this process.

By encouraging the public, other scientists and decision-makers to visit the URL, they can see for themselves the RD&D that is being done. They can experience the level of isolation provided by the overburden and meet with the scientists and engineers involved, ask their questions and raise any concerns that they may have. This can build a confidence in the GDF programme that no amount of reports can achieve.

Most URLs currently in operation have a public affairs programme as part of their URL activities. The Äspö Hard Rock Laboratory has a ramp access along which tour buses transport groups of visitors to the underground facility. At the surface there is also an exhibition building with explanations about geological disposal and the work done at the URL (Fig. 14). The surface buildings are purposely designed to look more like a local farm than an underground mine or industrial buildings.

International collaboration

Opening a URL to international collaboration brings together qualified personnel from multiple countries and leads to a broader knowledge base. It also promotes the exchange of ideas and the the dissemination of research results to a wider community. This openness to external experts and the alignment of the RD&D with what is happening internationally can contribute to the confidence of stakeholders in the programme. Conducting experiments together with international partners also helps to share some

Fig. 13. Students during the analysis of mine waters in the Josef Gallery. Source: courtesy of the Centre of Experimental Geotechnics, Czech Technical University in Prague.

Fig. 14. The Äspö Hard Rock Laboratory surface buildings contain an exhibition building and are designed to blend into the surroundings. Source: courtesy of SKB.

costs and can help avoid the duplication of expensive RD&D activities.

The Mont Terri Rock Laboratory is operated by the Federal Office of Topography Swisstopo (namely the Swiss Geological Survey), but international partners can use the facility to conduct experiments or participate in experiments conducted by others (Fig. 15). Currently, 22 partners from Canada, the USA, the UK, Europe, Switzerland and Japan are conducting research in the laboratory. Opalinus Clay is being investigated as a potential host rock for radioactive waste disposal. For a decade, research activities have expanded to assess if the clay can function as a cap rock for the geological storage of CO_2.

The future role of URLs

The roles URLs have played in geological disposal programmes have evolved over time (MacKinnon 2015). In the early days of URL development, 30–40 years ago, there was uncertainty around the technical feasibility of constructing large repositories in the host rocks being considered. By constructing a URL, the feasibility could be tested and excavation equipment and methods could be developed (Fig. 16). Another main priority of the first URLs was to examine the host rocks *in situ* and enhance the understanding of the key processes affecting post-closure safety.

Today, mature geological disposal concepts exist and there is confidence that these concepts are safe and effective. Underground research laboratory activities therefore focus more on increasing confidence by large-scale demonstration experiments, optimizing the equipment and techniques for specific site conditions, developing data for validating numerical modelling capacity and reducing uncertainties in the safety case.

What will be the role of URLs once geological disposal facilities are being operated? Today, there is only one geological disposal facility for long-lived

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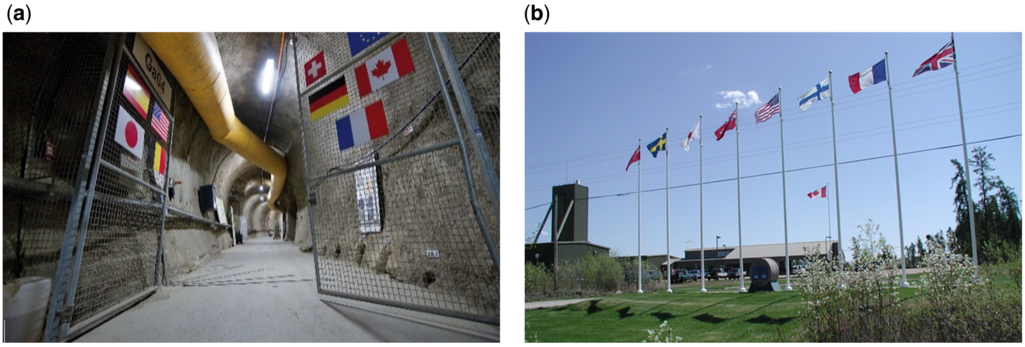

Fig. 15. Most URLs, such as (**a**) Mont Terri Rock Laboratory and (**b**) Whiteshell URL, have been used to conduct experiments together with international partners. Source: (a) courtesy of Swisstopo and (b) courtesy of AECL.

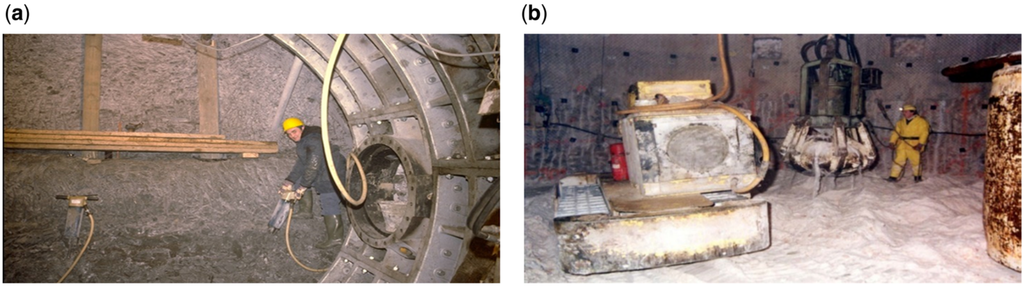

Fig. 16. (**a**) Manual excavation of the first gallery of the HADES URL in 1984 and (**b**) sinking of the shaft of the Gorleben URL in 1986. Source: (a) courtesy of ESV EURIDICE and (b) courtesy of BGE.

waste in operation: the WIPP facility in the USA. This means that we can only speculate, but it can be foreseen that URLs can still play an important role in the geological disposal programme.

We can expect to see pilot facilities being constructed as part of the repository. These facilities will be used to test and demonstrate at a representative scale and in similar conditions the equipment and methods that will be used for waste emplacement and repository closure. These pilot tests can also be set up to monitor the performance of the host rock or the EBS components. This monitoring may not be possible or desirable in the actual repository, especially when using intrusive means that could cause the monitoring tools to compromise or disrupt the repository. The ONKALO® URCF fulfils such a role for the Finnish GDF (Fig. 17).

The URL may also be used during disposal facility operation to test facility closure and to train personnel. This can even be useful after repository closure if, for example, the retrieval of the waste is considered. Testing and developing ways for doing this can be done in the URL.

Furthermore, the need to inform and engage with stakeholders and the public in particular will remain. As explained, URLs offer an excellent environment to show and explain what geological disposal is about and why this can offer a suitable and safe solution for the long-term management of radioactive waste.

Over recent decades several URLs have been constructed and several have already been closed. Will we see new URLs being constructed in the following years or decades from countries that are at the start of their geological disposal programme?

NO RWM, the National Operator for Radioactive Waste Management in the Russian Federation, plans to create a URL in the Nizhnekanskiy granitoid massif (Middle Siberia) (Fig. 18). The URL will be used to characterize the rock massif, optimize the EBS, work out how the radioactive waste management operations can be done and demonstrate operational safety. The URL will consist of three vertical shafts and a total of 5000 m of galleries excavated at a depth of between 450 and 525 m. The construction of the surface facilities has already started and the

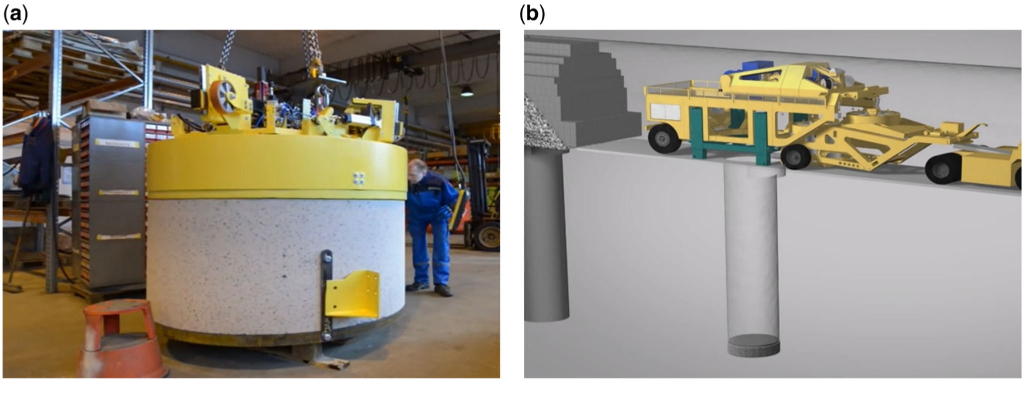

Fig. 17. POSIVA has used the ONKALO® URCF to test their Buffer Installation Device: (**a**) prototype of the device and (**b**) drawing of the device in action in the ONKALO® URCF. Source: POSIVA.

Fig. 18. Site of the National Operator for Radioactive Waste Management (NO RWM) in the Russian Federation's planned URL in Middle Siberia. Source: courtesy of NO RWM.

excavation of the underground facilities is expected to start in 2022.

In Germany, the so-called 'Site Selection Act' requires that BGE, the implementer of a deep geological repository (DGR) for high level waste, bases its recommendation for a site on the underground exploration of at least two distinct sites. The corresponding site-specific data and the site-specific design form the basis for the safety analyses, which are reviewed against the legal requirements and criteria and which will inform the government's siting decision.

Also in the Republic of Korea, a URL is one of the legal requirements for implementing a DGR. The URL has to demonstrate the suitability of the site and the feasibility and long-term performance of a disposal system. The Korea Radioactive Waste Agency (KORAD) is therefore expected to develop a site-specific URL in future.

The need for generic URLs is more specific to each national context. Our general understanding of the science and technology underlying geological disposal is well developed today and countries increasingly have the option to explore opportunities for international collaboration in existing URLs. Nevertheless, developing a generic URL provides value to a range of objectives, such as for competence development, stakeholder involvement and as a visible focal point for the national DGR programme. These may be particularly important if the site selection process of the national DGR programme does not seem to be making progress. In such a context, the visibility that a generic URL gives to the national DGR programme may allow maintainance of the momentum needed for programme development.

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References

Bastiaens, W. and Bernier, F. 2006. 25 years of underground engineering in a plastic clay formation: the HADES underground research facility. *Proceedings of the 5th*

International Conference of TC28 of the ISSMGE on Geotechnical Aspects of Underground Construction in Soft Ground, 15–17 June 2005, Amsterdam.

Blechschmidt, I. and Vomvoris, S. 2017. Relevance of underground rock laboratories for deep geological repository programs. *In*: Ahn, J. and Apted, M.J. (eds) *Geological Repository Systems for Safe Disposal of Spent Nuclear Fuels and Radioactive Waste*. Woodhead Publishing Series in Energy, **9**. Woodhead, Oxford, 113–142.

Chandler, N. 2003. Twenty years of underground research at Canada's URL. *WM'03 Conference*, 23–27 February, Tucson AZ.

Delay, J., Bossart, P. *et al*. 2014. Three decades of underground research laboratories: what have we learned? *Geological Society, London, Special Publications*, **400**, 7–32, https://doi.org/10.1144/SP400.1

Fujita, T., Nakayama, M., Tanai, K. and Sugita, Y. 2014. Plan of full-scale experiment on engineered barrier system in Horonobe Underground Research Laboratory. *International Conference on the Performance of Engineered Barriers*, 6–7 February, Hannover.

IAEA 2001. *The use of Scientific and Technical Results from Underground Research Laboratory Investigations for the Geological Disposal of Radioactive Waste*. IAEA-TECDOC-1243. IAEA, Vienna.

IAEA 2022. *Communication and Stakeholder Involvement in Radioactive Waste Disposal*. IAEA Nuclear Energy Series No. NW-T-1.16. IAEA, Vienna, https://www.iaea.org/publications/13590/communication-and-stakeholder-involvement-in-radioactive-waste-disposal

IAEA 2023. *The Management of Site Investigations for Radioactive Waste Disposal Facilities*. IAEA Nuclear Energy Series No. NW-T-1.40 [Preprint]. IAEA, Vienna, https://preprint.iaea.org/search.aspx?orig_q=RN:54010081

KAERI 2016. *Long-term corrosion of a copper canister in engineering barrier environment*, KAERI/TR-6470/2016.

MacKinnon, R.J. 2015. *The use of underground research laboratories to support repository development programs: A roadmap for the underground research facilities network*. SAND2015-9427. Sandia National Laboratories, Albuquerque, NM.

Matray, J.M., Savoye, S. and Cabrera, J. 2007. Desaturation and structure relationships around drifts excavated in the well-compacted Tournemire's argillite (Aveyron, France), *Engineering Geology*, **90**, 1–16, https://doi.org/10.1016/j.enggeo.2006.09.021

Mayer, S., Bergmans, A., Garcia-Sineriz, J.L., Breen, B.J. and Jobmann, M. 2012. Monitoring developments for safe repository operation and staged closure. The International MoDeRn Project. *Waste Management Conference 2012*, 26 February to 1 March, Phoenix, AZ.

NEA 2013. *Underground research laboratories (URLs)*, NEA report no. 78122, Radioactive waste management, NEA/RWM/R (2013)2, February, http://www.oecdnea.org

POSIVA 2012. *Rock suitability classification – RSC 2012*. POSIVA report 2012-24.

Schäfer, T., Seher, H. *et al*. 2009. The Colloid Formation and Migration (CFM) project at the Grimsel Test Site (Switzerland): results from the homologue tests. *Geochimica et Cosmochimica Acta*, **73**, A1168–A1168.

SKB 2015. *Äspö Hard Rock Laboratory: Annual Report 2014*. SKB TR-15-10, https://www.skb.com/publication/2482068/TR-15-10.pdf

Van Marcke, P., Li, X.L., Bastiaens, W., Verstricht, J., Chen, G., De Preter, P. and Leysen, J. 2013. *The design and installation of the PRACLAY In-Situ Experiment*, EURIDICE Report 13-129, https://www.euridice.be/sites/default/files/scientific/PRACLAY%20experiment%20Design%20and%20Installation%20Report%2060dpi.pdf

Vasicek, R. and Svoboda, J. 2009. The Josef Underground Educational Facility – a new training opportunity for students of geotechnics. *Proceedings of the ICEE & ICEER 2009 Korea, Engineering Education and Research under Knowledge Based Society*, 23–28 August, Seoul.

Wang, J., Chen, L., Su, R. and Zhao, X . 2018. The Beishan underground research laboratory for geological disposal of high-level radioactive waste in China: planning, site selection, site characterization and in situ tests. *Journal of Rock Mechanics and Geotechnical Engineering*, **10**, 411–435, https://doi.org/10.1016/j.jrmge.2018.03.002