Radioactive Waste Management and Decommissioning
NEA/RWM/R(2023)2
December 2024
www.oecd-nea.org

Underground Research Laboratories (URLs) – 2024 Update

OECD
BETTER POLICIES FOR BETTER LIVES

NEA
NUCLEAR ENERGY AGENCY

Nuclear Energy Agency

NEA/RWM/R(2023)2

Unclassified **English text only**

19 December 2024

NUCLEAR ENERGY AGENCY

Radioactive Waste Management Committee

Underground Research Laboratories (URLs) – 2024 Update

This document is available in PDF format only.

JT03557721

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

The OECD is a unique forum where the governments of 38 democracies work together to address the economic, social and environmental challenges of globalisation. The OECD is also at the forefront of efforts to understand and to help governments respond to new developments and concerns, such as corporate governance, the information economy and the challenges of an ageing population. The Organisation provides a setting where governments can compare policy experiences, seek answers to common problems, identify good practice and work to co-ordinate domestic and international policies.

The OECD member countries are: Australia, Austria, Belgium, Canada, Chile, Colombia, Costa Rica, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Türkiye, the United Kingdom and the United States. The European Commission takes part in the work of the OECD.

OECD Publishing disseminates widely the results of the Organisation’s statistics gathering and research on economic, social and environmental issues, as well as the conventions, guidelines and standards agreed by its members.

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1 February 1958. Current NEA membership consists of 34 countries: Argentina, Australia, Austria, Belgium, Bulgaria, Canada, Czechia, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, Norway, Poland, Portugal, Romania, Russia (suspended), the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Türkiye, the United Kingdom and the United States. The European Commission and the International Atomic Energy Agency also take part in the work of the Agency.

The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes;
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management and decommissioning, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

Acknowledgements

The Nuclear Energy Agency (NEA) sincerely thanks all the participants of the Programme Committee for this updated version of the report on underground research laboratories: Hiroyuki Umeki (Nuclear Waste Management Organization of Japan, or NUMO), Jessica Palmqvist (Swedish Nuclear Fuel and Waste Management Company, or SKB), Akari Sato (Japan's Ministry of Economy, Trade and Industry, or METI), Kazuhei Aoyagi (METI), Atsushi Saiga (METI) and Satoru Yasuraoka (METI). The NEA also thanks its colleagues at the International Atomic Energy Agency, and in particular Stefan Mayer, for updating the Underground Research Laboratory presentation tables. Gérald Ouzounian (Nucadvisor) ensured the preparation of this report and was supported in his work by Rebecca Tadesse, Head of the NEA Division of Radioactive Waste Management and Decommissioning (RWMD); by Vladimir Lebedev, Deputy Head, RWMD; by Yuko Maehashi, Consultant, RWMD; and by Soufiane Mekki, Radioactive Waste Management Specialist, RWMD.

Foreword

In 2001, the Radioactive Waste Management Committee (RWMC) of the Nuclear Energy Agency (NEA) published a report describing the role of underground research laboratories (URLs) in nuclear waste disposal programmes and their value in building confidence in national programmes. A subsequent report published in 2013 built on the 2001 document and incorporated the documentation then available on the URLs. The strategic perspectives of NEA countries on URLs were presented in an easily accessible document for an audience of both specialists and non-specialists.

Given the multiple complex challenges of geological disposal, the RWMC considered that an update was necessary, and that it was appropriate to consider intensifying international co-operation, to the benefit of member countries. This report therefore presents recent advances in geological disposal programmes and discusses the contributions of international co-operation in experimentation programmes in the URLs. The report was approved by the NEA Radioactive Waste Committee on 8 September 2023 by the written procedure.

As the URL activities continue to evolve, this report complements the information provided previously by the NEA by integrating information directly from NEA member countries as well as from other countries in a strategic framework.

Table of contents

List of tables

List of figures

List of boxes

List of abbreviations and acronyms

AECL	Atomic Energy of Canada Limited
AI	Artificial intelligence
Andra	National Agency for Radioactive Waste Management (France)
BfS	Federal Office for Radiation Protection (Germany)
DBE	German company for the construction and operation of waste repositories
Enresa	Spanish radioactive waste management agency
ESF	Exploratory Studies Facility, Yucca Mountain (United States)
EIG EURIDICE	Economic Interest Grouping – European Underground Research Infrastructure for Disposal of Nuclear Waste in Clay Environment (Belgium)
GSF	Helmholtz Zentrum München, German Research Centre for Environmental Health
GTS	Grimsel Test Site (Switzerland)
HADES	High-Activity Disposal Experiment Site (Mol, Belgium)
HIP	Horonobe International Project
IAEA	International Atomic Energy Agency
ILW	Intermediate-level waste
IRSN	Nuclear Radioprotection and Safety Institute (France)
JAEA	Japan Atomic Energy Agency (former JNC)
LLW	Low-level waste
Nagra	National Co-operative for the Disposal of Radioactive Waste (Switzerland)
NEA	Nuclear Energy Agency
OECD	Organisation for Economic Co-operation and Development
Posiva	Finnish company with the task of handling the final disposal of the spent nuclear fuel
PURAM	Public Agency for Radioactive Waste Management (Hungary)
QA / QM	Quality assurance / quality management
R&D	Research and development
SEDE	Co-ordinating Group on Site Evaluation and Design of Experiments for Radioactive Waste Disposal (NEA)
SF	Spent fuel
SNHGS	Swiss National Hydrological and Geological Survey
SKB	Nuclear Fuel and Waste Management Company (Sweden)
TRU	Transuranic waste
URF	Underground Research Facility (Mol, Belgium)

1. Introduction

The concept of engineered geologic disposal has been developed for the safe long-term management of high-level and of long-lived radioactive waste. This involves the placement of radioactive waste in deep underground repositories that provide long-term safe containment and isolation and protect humans and the environment, as stated in the NEA Collective Statement (NEA, 2008). A nuclear waste repository takes decades to develop and uses the best available technologies and engineering design. Throughout its development, the feasibility, safety and appropriateness of the proposed system must be discussed with all stakeholders with the goal of developing a common understanding of the concerns and the approach for resolution. These discussions are needed before a decision can be made on having a repository and the development process can progress. Several important decisions underpinned by safety reviews must then be taken before the licensing of the final closure of a repository, and there is a commitment on the part of involved stakeholders to continuously improve the technical solutions in a virtuous process of optimisation.

Practical demonstrations of key technical elements are required to show the robustness of the proposed design as well as to establish confidence. Underground research laboratories (URLs) play an important and multi-faceted role in these scientific assessments and demonstrations by providing a realistic environment for characterising and testing the selected technical approaches and materials. To demonstrate operational safety, acquire geological information at a repository scale and show constructional and operational feasibility, only URLs can provide reliable *in situ* data, with a relatively longer duration of experiments than in geological disposal under construction or in operation. URLs can also enhance the participation of the general scientific community and increase confidence among both technical and non-technical stakeholders.

Many nuclear waste management programmes have progressed over the past decade. Construction work on the deep geological repository site has started in Finland, the construction licence for one in Sweden has been granted, and in France the application for a site has been submitted to the regulator. The programmes in Switzerland and Canada are also progressing, with candidate sites for deep geological repositories (DGRs) now identified. Other countries, such as Germany, Japan, and the United Kingdom, are preparing for new phases.

All these programmes have made extensive use of URLs for research and development work, including in the optimisation of design elements, and have conducted or planned detailed site investigations through site-specific URLs. Other radioactive waste management programmes are commissioning or considering new URLs as integral components of staged implementation of geological disposal. New URLs are also being planned to further optimise the implementation of geological disposal. The workshop organised in Horonobe, Japan, in November 2022 was an opportunity to synthesise the contributions of URLs and to prepare the Horonobe International Project (HIP); the link to the corresponding report including the executive summary is provided in Appendix B (NEA, 2024).

In 2001, the Radioactive Waste Management Committee (RWMC) of the Nuclear Energy Agency (NEA) published a report describing the role of URLs in nuclear waste disposal programmes and their value in building confidence in national programmes (NEA, 2001). A later report, published in 2013 (NEA, 2013), built on the 2001 document and incorporated the documentation then available on the URLs. The strategic perspectives of

NEA countries on URLs were presented in an easily accessible document for an audience of both specialists and non-specialists.

Given the complex and multiple challenges of geological disposal, the RWMC considered that an update was necessary, and that it was appropriate to consider intensifying international co-operation to the benefit of member countries. This report therefore presents recent advances in geological disposal programmes and discusses the contributions of international co-operation in experimentation programmes in URLs.

As the URL activities continue to evolve, this report complements the information provided in the earlier version (NEA, 2013) by integrating information directly from NEA member countries as well as from other countries in a strategic framework.

This document provides an updated overview of:

- The purposes and types of URLs that have been developed and are in operation or that planned in NEA member countries and other countries (Chapter 2);
- The roles of URLs in repository development (Chapter 3);
- The aspects to consider when planning a URL during stepwise repository development (Chapter 4);
- The experience with URLs in the last decade (Chapter 5);
- Opportunities and benefits of international co-operation in relation to URLs (Chapter 6).

Details on the URL programmes can be found on their websites as listed in Appendix A.

Terminology

While the terminology used in different national waste management programmes may vary, the following key terms are often associated with URL activities and are therefore defined at the onset:

- *(Site) Characterisation*. In situ investigations to provide basic understanding of the geologic, hydrogeologic, geochemical, structural and mechanical properties of the host rock.
- *Demonstration*. Illustration, at full or reduced scale and under real and/or simulated repository conditions, of the feasibility of the repository design or of the behaviour and performance of various components of the repository. For example, demonstrations of sealing, waste emplacement or retrieval techniques. Demonstration may also comprise disposal trials of actual radioactive waste in facilities (i.e. pilot facilities) in which the necessary licences are required.
- *Testing*. A broad term to cover various activities during the development of a repository in order to evaluate in situ: i) the feasibility and performance of certain operations, such as excavation, disposal, sealing and closure techniques; ii) the performance of engineered materials.
- *Technology development*. The development of equipment, techniques and expertise for site characterisation, testing, monitoring for repository construction, waste emplacement (and retrieval), construction of engineered barriers, and repository closure.

2. Purpose, types of URL and existing facilities

What is a URL?

A URL is an underground facility used for site characterisation, testing activities, technology development and demonstration activities in support of the development of deep geological repositories for radioactive waste.

URLs are located in geological environments such as granite, salt, clay/shale or volcanic tuff that are considered to be suitable for a repository. They may be constructed at depths of up to a few hundred metres, depending on the activities that are to be conducted at the URL. A URL may be an elaborate, purpose-built facility in which large research programmes are carried out over many years, or a simpler facility, for example one attached to existing underground excavations, in which specific investigations are made.

Regardless of the type being developed in a repository programme, all URLs play a prominent role in the development of the safety case for a repository and serve to enhance confidence at the various stages of decision-making and strategic planning of waste disposal.

Given the time required for the development of geological repositories, the role of URLs for the training of specialists as well as for the transmission of know-how from generation to generation is essential.

Purpose of URLs

The main purpose of URLs is to further the repository development process by facilitating research activities under an environment similar to the repository but with less disturbance.

To that effect, URLs are used to:

- develop the technology and methodology required for underground experimentation;
- provide data to understand the behaviour and assess the performance of the repository system and of its interactions;
- demonstrate the robustness of the design and show the potential areas of optimisation of engineering components and processes;
- produce and verify the information needed for safety demonstrations in support of licence applications for geological disposal;
- demonstrate the feasibility of construction and operation of the future geological repository;
- support the implementation of new, advanced technologies (testing, developing methodologies, training personnel, etc.);
- train personnel for the safe operation of a future repository;
- build confidence among stakeholders by increasing understanding of the important processes governing repository performance.

Types of URL

Two broad categories of URLs can be distinguished:

- *Generic URLs:* facilities that are developed for generic research and testing purposes at a site that will not be used for waste disposal, providing information that may support disposal elsewhere.
- *Site-specific URLs*: facilities that are developed at locations that are being considered as potential sites for waste disposal; these facilities may be a precursor to, or represent the initial stage of, developing a repository at the site.

Generic URLs

Generic URLs are developed to gain general experience of site characterisation and underground construction techniques, model testing and verification of investigation and measurement techniques. They are not built in a specifically selected host rock formation with the intent to closely match a repository. Generic URLs are useful in the early stages of repository programmes, especially to develop skills and methods. For example, generic field investigations were carried out at the Swiss Grimsel test site long before the selection of a particular host geological formation. Specific investigations were later launched in the Mont Terri Road tunnel to study a clayey formation, which has since been considered as a host rock for geological repository in Switzerland, on another site.

The establishment of a URL requires significant investments in infrastructure support, in terms of excavation, construction and maintenance of underground services and safety. For this reason, many generic URLs operating in NEA member countries have been developed from existing excavations such as mines and tunnels. The advantages of using an existing mine or underground access include that: i) it makes use of the initial excavation and existing mine maintenance and safety infrastructure; ii) it is easier to get planning permissions to extend work in an existing mine or tunnel as opposed to developing a new site. URLs that are built on existing infrastructures benefit from cost-saving opportunities to gain experience in techniques relevant to site characterisation, facility construction, operation and site closure. The trade-off of using an already existing facility is that the pre-existing constructions often do not correspond well to the conditions of the actual repository, and therefore are mainly suitable for studies required in the early stages of repository development programmes.

Generic URLs built in a geological environment similar to that of the future repository have the advantages of more control, particularly in the areas of obtaining preconstruction (undisturbed site) data, enhancing the design of the repository and its excavation and construction techniques, as well as improving the overall operation of the underground facilities. These URLs also contribute to confidence building as they effectively relate the predictions made of underground conditions from surface-based investigations with observations resulting from underground studies. Furthermore, a purpose-built generic URL can be designed to accommodate visitors to communicate with the public regarding the developmental progress of the repository programme and to build confidence. The trade-off is that these purpose-built URLs require substantial resources for the excavation, construction and operation of the underground services.

As new technologies that could be applied in DGR concepts (e.g. robotic systems, artificial intelligence (AI), digital twins or new materials) are developing rapidly, the URL can be used to support any new applications by testing and developing methodologies, training personnel and other activities. Also, these new activities could be followed with a demonstration to stakeholders of the improved safety parameters and provide additional educational capacities. Relevant R&D programmes can even be conducted during the DGR's operation to ensure the smooth integration of new technologies.

New opportunities for R&D in URLs are connected to plans to build small module reactors (SMRs) and other advanced reactors and the appearance of new types of spent fuel (SF) and radioactive waste (RW). The URLs can be used to prepare the adaptation of DGR concepts to these new types of disposed-of containment.

Tables 2.1 and 2.2 list the generic URLs built on pre-existing underground excavations and the purpose-built generic URLs in various NEA member countries, respectively.

Site-specific URLs

In cases where a repository programme has identified one or more potential repository sites, a site-specific URL may be developed to gain information and experience directly applicable to the future repository. The URL may be constructed either adjacent to, or within, the proposed repository locality, and if repository development proceeds, the URL may be partially or completely subsumed within the repository. Shafts and access ways to the URL may provide secondary or even primary access routes to the repository, if they have been designed as such.

Site-specific URLs are often used to confirm the suitability of the potential geologic environment, guiding the site-specific layout and design of the repository, demonstrating the various technological operations under site-specific conditions, and allowing continuing R&D programme during the disposal operations. As with generic URLs, general research and development may also be carried out at site-specific URLs, provided that these activities do not adversely affect the disposal operations or the future safety of disposal at the site. A site-specific URL may stay open after its associated repository is closed, providing opportunities to test methods and approaches for long-term monitoring of repository performance. Table 2.3 provides a list of site-specific URLs in NEA member countries.

Table 2.1. Generic URLs in NEA member countries, built on pre-existing underground excavations

URL	Host rock, location, depth	Managing organisation/remarks	Countries and institutions co-operating with research
Asse Mine	*Host rock* - *Permian rock salt anticline.* *Location* *Wolfenbuettel/Braunschweig region of Germany.* *Depth* - *Mining levels between 490-925 m. Mined cavern at 950 m.* - *Waste emplacement at 511 m and 750 m levels.*	*Managing organisation* - *GSF (now Helmholtz Zentrum München).* - *The operator was BfS from 2009 to 2017, and BGE since 2018* *Remarks* - *Galleries in former potash and rock salt mine. Demonstration facility for waste disposal from 1965-1978. R&D facility until 1997. Backfilling of unused excavations under way. [Note: The Asse Mine is no longer a URL. During its operation period, considerable amounts of L&ILW were emplaced. The mine is now a radioactive waste repository under the responsibility of the Federal Office for Radiation Protection (BfS), Germany. From 2009 to 2017, BfS has been operating the Asse Mine under nuclear law which has more pronounced requirements than mining law. BGE has been the operator since 2018 – and is also charged with engineering and proposing an approach to retrieve emplaced RW, with licensing procedure to retrieve waste started in 2020.]*	
Tono Mine	*Host rock* - *Neogene sedimentary rock.* *Location* - *Gifu prefecture, central Japan.* *Depth* - *130 m.*	*Managing organisation* - *JAEA.* *Remarks* - *Galleries in former uranium mine. Operated 1986-2004.*	France, Switzerland.
Kamaishi Mine	*Host rock* - *Granite.* *Location* - *Iwate Prefecture, north-eastern Japan.* *Depth* - *300-700 m*	*Managing organisation* - *JAEA.* *Remarks* - *Galleries in former iron-copper mine. Operated 1988-1998.*	Switzerland.

Table 2.1. Generic URLs in NEA member countries, built on pre-existing underground excavations (cont.)

URL	Host rock, location, depth	Managing organisation/remarks	Countries and institutions co-operating with research
Stripa Mine	*Host rock* - *Granite.* *Location* - *Near the Guldsmedshyltan region of Sweden.* *Depth* - *338-410 m*	*Managing organisation* - *SKB.* *Remarks* - *Galleries in former iron mine. Operated 1976-1992.*	Canada, Finland, France, Japan, Spain, Switzerland, United States. The International Stripa Project was launched in 1980, supported by the NEA.
Grimsel Test Site (GTS)	*Host rock* - Granite. *Location* - In the Grimsel region of Switzerland. *Depth* - 420-520 m.	*Managing organisation* - Nagra. Remarks - Gallery from a service tunnel of a hydroelectric project. Operating since 1984.	Czechia, Finland, France, Germany, Japan, Korea, Spain, Sweden, United Kingdom, United States, EC and the IAEA URF network.
Mont Terri	*Host rock* - Opalinus clay (hard clay). *Location* - In the Mont Terri region of north western Switzerland. *Depth* - 250-320 m.	*Managing organisation* *Swiss Geological Survey (SGS), a Department within Swisstopo.* *Remarks* - Gallery from a highway tunnel. Initiated in 1995.	Belgium, Canada, France, Germany, Japan, Spain, United Kingdom, United States.
Olkiluoto Research Tunnel	*Host rock* - Granite (tonalite). *Location* - In the Länsi-Suomi region of Finland. *Depth* - 60-100 m.	*Managing organisation* - Posiva. *Remarks* - Tunnel adjacent to the Olkiluoto repository for LLW. Operating since 1992. Research relevant to spent fuel disposal at this and other sites in Finland.	Sweden.
Climax	*Host rock* - Granite. *Location* - Nevada Test Site, United States. *Depth* - 420 m.	*Managing organisation* - US-DOE (Department of energy). *Remarks* - Drift mined from existing excavations. Spent fuel disposal experiments conducted in 1978-1983.	

Table 2.1. Generic URLs in NEA member countries, built on pre-existing underground excavations (cont.)

URL	Host rock, location, depth	Managing organisation/remarks	Countries and institutions co-operating with research
G-Tunnel	*Host rock* • Tuff. *Location* • Nevada, United States. *Depth* • > 300 m.	*Managing organisation* • DOE. *Remarks* • Tunnel of weapons-testing excavations. Operated 1979-1990.	
Amelie	*Host rock* • Bedded salt. *Location* • Alsace, France. *Depth* • 630-650 m	*Managing organisation* • Andra. *Remarks* • Galleries in potash mine. Operated 1986-1992.	Co-operation in the framework of an CCE programme (mid 1980s), in a joint task force Andra, DBE, GSF, Enresa.
Fanay-Augères	*Host rock* • Granite. *Location* • Limousin, France. *Depth* • 170 m	*Managing organisation* • IRSN. *Remarks* • Galleries in uranium mine. Operated 1980-1990.	
Tournemire Facility	*Host rock* • Sediments (hard clay). *Location* • Auvergne, France. *Depth* • 250 m.	*Managing organisation* • IRSN. *Remarks* • Former railway tunnel and adjacent galleries. Operating since 1990.	Canada, IAEA URF network.
Josef Underground Research Center	*Host Rock* • Geological continuum is made up of Jílové zone volcanic (basalts, andesites, rhyolites) and sedimentary (hornfels) rock types and their combinations (tuffs, tuffites) characterised by younger intrusive rock types (granodiorites, albitic granites) *Location* • Central Bohemia, Czechia *Depth* • 30 to 180 m of rock cover	*Operator* • Centre of Experimental Geotechnics; Faculty of Civil Engineering; Czech Technical University in Prague *Remarks* • Former network of galleries for gold survey (Josef Gallery), sealed 1991 to 2005. Operating as generic URF with teaching and experiments since 2007.	

Table 2.2. Purpose-built generic URLs in NEA member countries

URL	Host rock, location, depth	Managing organisation/remarks	Countries and institutions co-operating with research
High-Activity Disposal Experiment Site Underground Research Facility (HADES-URF)	*Host rock* • Boom clay (plastic clay). *Location* • Mol/Dessel, Belgium. *Depth* • 224 m.	*Managing organisation* • EIG EURIDICE. *Remarks* • Shaft sinking began 1980, operating since 1984 and the extension of the lab with the test drift (1987), the construction of the second access shaft (1997-1999) and the realisation of the connection gallery (2001-2002).	France, Germany, Japan, Netherlands, Spain,, Switzerland.
AECL Whiteshell Underground Research Laboratory	*Host rock* • Granite. *Location* • Lac du Bonnet, Pinawa, Manitoba, Canada. *Depth* • 240-420 m.	*Managing organisation* • AECL. *Remarks* • Operated 1984-2006. URL officially closed on 17 November 2010. *Special note* • Monitoring via in situ shaft seal instrumentation continues, with data acquisition conducted from the surface of the closed access shafts.	Finland, France, Japan, Sweden, United States.
Mizunami Underground Research Laboratory (MIU)	*Host rock* • Granite. *Location* • Gifu Prefecture, central Japan. *Depth* • Research galleries at 300 m and 500 m	*Managing organisation* • JAEA. *Remarks* • "Phase I" of the MIU project was initiated in 1996. The construction site had been changed in 2002, from Shobasama to city-owned land, where construction then started. • Excavation of two shafts started in 2003 and R&D was developed during excavation since 2004, and R&D at research gallery at 300 m and 500m level since 2010. • MIU underground facilities backfilled by 2022 – end of land lease 16 January 2022.	Korea, Switzerland, United States.

Table 2.2. Purpose-built generic URLs in NEA member countries (cont.)

URL	Host rock, location, depth	Managing organisation/remarks	Countries and institutions co-operating with research
Horonobe Underground Research Laboratory	*Host rock* - Neogene sedimentary rock. *Location* Hokkaido *Depth* - Research galleries in operation at 140 m, 250 m and 350 m. To be constructed at 500 m.	*Managing organisation* - JAEA. *Remarks* - URL construction started in 2005 and ended to 350 m depth in 2014. Extension of URL to 500m to be started in April 2023. R&D during excavation ongoing since 2005 and R&D at research galleries has been ongoing since 2010.	Development of the HIP "Horonobe International Project" initiated in February 2023 with administrative support of the NEA (see Appendix B).
Äspö Hard Rock Laboratory	*Host rock* - Granite. *Location* - Oskarshamn, Sweden. *Depth* - Several depths between 200-450 m.	*Managing organisation* - SKB. *Remarks* - Operating since 1995. Activities at Äspö have received a significant amount of experience and knowledge gained from the Stripa Mine.	Canada, Finland, France, Germany, Japan, Spain, Switzerland, United Kingdom, United States.
Busted Butte	*Host rock* - Bedded tuff, Calico Hills Formation. *Location* - Yucca Mountain, Nevada, United States. *Depth* - 100 m.	*Managing organisation* - US DOE. *Remarks* - Operating since 1998. - All work suspended since 2010.	
Korea Underground Research Tunnel (KURT)	*Host rock* - Granite. *Location* - Daejon, Korea. *Depth* - 120 m.	*Managing organisation* - KAERI. *Remarks* - Operating since 2006.	

Table 2.3. Site-specific URLs in NEA member countries

URL	Host rock, location, depth	Managing organisation/remarks	Countries and institutions co-operating with research
ONKALO	*Host rock* • Granite (tonalite). *Location* • Eurajoki, Finland. *Depth* • 422 m for disposal, 437 m technical level below surface	*Managing organisation* • Posiva. *Remarks* • Received a building permit for the facility in August 2003 and excavation began in 2004. Research niches constructed in 2009. First demonstration tunnels constructed at -422m in 2011. • Commissioning test scheduled to begin in 2023.	
Gorleben	*Host rock* • Salt dome. *Location* • Lower Saxony, Germany. *Depth* • About 900 m below ground.	*Managing organisation* • BfS, operator being BGE *Remarks* • Shafts constructed 1985-1990, moratorium between 2000 and 2010, resumption of underground site characterisation in 2010. Exploration stopped again in 2013 by decree of the Site Selection Act. • After first stage of selection, the Gorleben site had been screened out. Current objective is to decommission site.	
Konrad	*Host rock* • Limestone surrounded by Jurassic marls and covered by 300m of Lower Cretaceous Claystone formation *Location* • Germany; southeast Lower Saxony. *Depth* • 800-1 200 m below ground.	*Managing organisation* • BfS, operator being now BGE. *Remarks* • Galleries in former iron mine, operating as URL since 1980, licensed as a LLW/ILW repository since 2007, now converted into a repository for all kinds of solid radioactive waste with negligible heat generation.	
Morsleben	*Host rock* • Salt dome. *Location* • Saxony-Anhalt, Germany. *Depth* • Several depths up to 525 m below ground.	*Managing organisation* • BfS, operator being now BGE. *Remarks* • Former salt and potash mine. • Disposal of LLW and ILW, operations 1971-1991 and 1994-1998. • Preparation for closure since 2001, with corresponding underground research. • Licensing for decommissioning pending.	

Table 2.3. Site-specific URLs in NEA member countries (cont.)

URL	Host rock, location, depth	Managing organisation/remarks	Countries and institutions co-operating with research
Pécs (Mecsek Mountain)	*Host rock* • Indurated clay, Boda Claystone Formation. *Location* • Hungary. *Depth* • 1 000 m.	*Managing organisation* • PURAM. *Remarks* • Former uranium mine, operated 1995-1999.	
Waste Isolation Pilot Plant (WIPP)	*Host rock* • Salt (bedded), Salado Formation. *Location* • Carlsbad, New Mexico, United States. *Depth* • 655 m.	*Managing organisation* • US DOE. *Remarks* • First purpose-built, site specific URL in undisturbed salt rock. • First facility with transition from URL to licensed geological disposal facility. • Operating since 1982, licensed transuranic (TRU) waste repository since 1999. • 1983-1995: large scale underground experiments. • 1999: first waste emplacement. • In parallel, URL experiments are being conducted.	Canada, France, Germany, Japan, Sweden, United Kingdom.
Exploratory Studies Facility (ESF)	*Host rock* • Welded tuff, Calico Hills Formation. *Location* • Yucca Mountain, Nevada, United States. *Depth* • 300 m.	*Managing organisation* • US DOE. *Remarks* • Construction of ESF started in 1995 and remained operational as URF 1995-2010. • In situ testing began in 1996; construction of an exploratory side tunnel completed in 1998. Operation suspended since 2010.	
Bure	*Host rock* • Shale (indurated clays), Callovo-Oxfordian Argillites. *Location* • Meuse/Haute-Marne France. *Depth* • Main levels 445 and 490 m.	*Managing organisation* • Andra. *Remarks* • Licensed for construction of a URL in November 1999. Construction starts 2000. Two shafts provide access to both levels at 445 and 490 m. • Operation still ongoing and the four main phases of RD&D evolved in close relation to the Cigéo project development. The full licence application for the Cigéo deep geological disposal facility was submitted in 01/2023. The URL is not allowed to receive any waste and will not be integrated in the repository.	Germany, Japan, Switzerland.

3. The role of URLs in repository development

More than 50 years of work on specific scientific issues related to URLs has led to generic and site-specific URLs playing distinctly different roles, even though the type of work carried out may in many ways be similar. The essential difference between generic and site-specific URLs is related to whether the emphasis is placed on developing an understanding of the processes that occur in rocks, or on the collection of site-specific data. Studies or experiments which might compromise the integrity of the geological barrier at the site-specific URL or could delay the initial onset of repository construction could be carried out at a generic URL. The roles of generic and site-specific URLs are summarised in Table 3.1.

Table 3.1. Roles of generic and site-specific URLs

Generic URL	Site-specific URL
Development and testing of technology and methodology – test methods for characterisation, construction techniques, monitoring. *Development of understanding of processes and collection of generic data for safety assessment* – sensitivity of rock mechanics, host rock-barrier properties and their interaction. *Concept testing and demonstration* – testing of disposal design concept and alternatives, operational options, demonstration of industrial-scale projects. *Building confidence and fostering international co-operation* – experts from different disciplines interact to build technical confidence, develop experience among international professional communities, interaction between various stakeholders and interested public. *Development of skills and transmission of knowledge and know-how* – professionals in charge of geological disposal have the opportunity to be trained there to be operational during the experimentation phases, then later during disposal. The activities in generic URL also make it possible to maintain the knowledge and the know-how to transmit it to later generations who have to develop the disposal, close it and ensure monitoring.	*Evaluation of site and confirmation* – characterisation of geosphere immediately adjacent to repository and development of upscaling rules. *Collection of site-specific data* – data required for performance assessments and for future optimisation of repository design, reduction in inherent conservatism in conceptual and safety assessment models. *Demonstration of technology and techniques* – monitoring of near-field responses of the repository for regulatory purposes, to address environmental impact assessment issues. *Testing of repository designs as well as other operational aspects* – testing the robustness of the EBS or other testing linked specifically to safety assessment requirements for licensing. *Building confidence* – demonstration of specific system design/techniques to regulators and the public.

The role of generic URLs

Generic URLs have been developed for a variety of reasons. The earlier URLs were developed to substantiate the initial repository concepts that had been designed for a disposal facility and to examine specific aspects of the near-field reactions. For example, the Stripa Mine project, organised by the NEA between 1980 and 1992, provided valuable geohydrological information on granitic rock at a depth of 350-400 m and developed technologies for measuring the thermodynamic, geophysical and geochemical properties of the Stripa granite. The experiments were also intended to support the development of models, their verification and their validation, with a view to having simulations that to cover very large time scales. Later URLs were developed for reasons such as to test and validate technologies that could reduce cost and/or simplify repository design without compromising safety (e.g. Äspö in Sweden). There are also URLs developed particularly to examine specific rock types as in the case of Mont Terri in Switzerland. The research at Mont Terri is primarily aimed at increasing the basic understanding of low-permeability, indurated argillaceous media, and is therefore not focused exclusively on studies related to deep disposal (Bossart P. and M.Thury, 2008). Other rock types that have been extensively studied through other generic URLs include crystalline rock, argillaceous clay and rock salt.

The generic URLs are generally located on sites for which the information and geological data could be valued for the disposal option proposed. Some generic URL sites are selected because they have amplified features that allow for better modelling support, and are therefore potentially less favourable than actual elimination sites (e.g. Äspö was selected partly due to its estimated fracture density being greater than one likely to be at a selected disposal site in Sweden). Other URL sites are chosen for the different rock characteristics from the proposed host formation, providing valuable comparisons between the preferred disposal option and the generic site (e.g. the German R&D programme includes experimental work at Mont Terri and Äspö). Finally, some generic URLs were developed with a view to developing knowledge and skills and are sometimes simply the result of opportunities arising (e.g. Tournemire or the KURT).

Generic URLs play a unique role and cannot be replaced by site-specific URLs in some cases. For example, experiments that are unfavourable to be performed in a site-specific URL (due to possible interference with repository construction or operation) can be carried out in a generic URL. Another factor to consider is the time required for certain experiments or technological developments and their demonstration. The URL can accommodate these circumstances while the GDR is under construction or in operation, subject to operational constraints.

The URLs, whether generic or specific, are also used to train and prepare teams for studies related to geological disposal and to learn how to set up and implement experiments and demonstrators. The transmission of information and know-how from one generation to the next also ensures continuity in the operations, including at the DGR.

The role of site-specific URLs

Work in site-specific URLs is sometimes considered as the continuation of a site-characterisation programme. As a site-characterisation programme continues and eventually reaches a stage when site-specific information is required (i.e. surface investigations cannot sensibly provide the required information or, when direct access to the relevant parts of the host rock is required, to make progress such as validation of models by in situ tests or optimisation of excavation techniques), a site-specific URLs can be considered. In designing a site-specific URL programme, it is crucial to minimise damage to the geosphere barrier (e.g. locate access routes to the URL where repository access would later be required) and to avoid a large number of boreholes drilled from the surface, except where they are subsequently assimilated by underground access. This is particularly important if the host rock has low permeability as obtaining reliable data using surface boreholes will be extremely difficult and specialised testing techniques will have to be used in situ.

The site-specific URL allows the acquisition of directly valued data for the demonstration of safety, as well as the validation of models in the most representative possible conditions. This is an undeniable asset for the quality of the safety case and for the confidence regulators will have in the demonstration for the DGR project. It is also a major asset in gaining the trust of stakeholders, including the general public.

4. The planning of a URL during stepwise repository development

Regardless of the type, URLs play a prominent role in the development of a repository. They provide a platform to obtain important scientific evidence to better understand the scientific aspects of repository development (such as the geological, hydrogeologic and geochemical characteristics of a site) and to prepare technical options (such as the design of the disposal cells, development of the EBS, or testing of machines for placing the waste packages). Understanding the sites makes it possible to model them, which will then allow simulations to assess the long-term performance of the DGR. The repository, considered as a whole system integrating the knowledge acquired as well as the technological choices for the disposal, gives rise to the safety case, the objective of which is to ensure the overall consistency and performance of the disposal. On the non-technical side, URLs enhance confidence building in the various stages of decision-making and strategic planning of waste disposal. In 2010, about 7 000 visitors at the Äspö facility were shown the research and full-scale testing carried out in a real environment for a spent fuel repository in Sweden. In France, the Bure URL welcomes more than 10 000 visitors per year. Underground laboratories are widely visited, both directly and increasingly by means of virtual visits (for example HADES in Mol, at www.euridice.be/en/content/virtueal-tour).

Stepwise repository development and supporting work in URLs

Repository development proceeds in stages which include planning, technical development and scientific research, siting, design, licensing, construction, operation, and eventual closure of the disposal facility, including dismantling. Developing a geological repository in a stepwise manner allows experience and information gained at each stage to be reviewed to confirm there is sufficient information to proceed to the next phase. For different stages of the repository development process, the URL activities listed below have been defined to achieve the required scientific/technical information.

Concept development:

- Research to understand the general characteristics and processes in relevant geologic environments to develop generic models of rock and hydrogeologic response, transport of contaminants, and overall repository performance. In the case of site-specific URLs, the models will also be site-specific.
- Initial development and testing of excavation techniques and material specifications, e.g. for rock support measures, backfill and sealing, and monitoring techniques.
- Testing of site characterisation techniques to ascertain their capabilities and accuracy under field conditions, specifically for the studied geological environment, but also more generally for different geological environments.

Site selection and characterisation:

- Characterisation, substantiation and confirmation of specific geologic environments or sites.
- Development of site models and testing against observed responses to experiments and to excavation in the URL.
- Identification of key uncertainties.
- Refinement of excavation techniques, material specifications and monitoring techniques.

Repository development:

- Development of the safety concept and the design for all repository phases (including closure).
- Development of waste emplacement, backfilling, closure (and retrieval) methods.
- Development of monitoring strategies.
- Refinement and testing of monitoring techniques.
- Testing and demonstration of waste handling equipment.
- Demonstration trial of waste emplacement, buffering, backfilling, sealing and retrieval.

Repository operation and closure:

- Continued refinement of techniques and instrumentation.
- Optimisation of repository construction, operation and waste emplacement techniques.
- Optimisation of backfilling and sealing, repository closure.
- Post-emplacement and post-closure monitoring.

URL planning and their limitations

When planning for a URL, the type of underground research facility required by a programme depends on various factors such as the research priorities, the repository developmental phase, and the budgets of the waste management programme. Factors to consider when designing generic and site-specific URL programmes are described in Table 4.1. Despite the many benefits that a waste management programme may gain from URLs, there are inherent limitations to testing in URLs. For instance, activities at a generic URL may involve invasive techniques in conducting their characterisation and R&D work. The extent of such damage may affect the design and construction of the site-specific URL. Other possible limitations for both URL types are presented in Table 4.2. While these limitations may potentially affect the extent and reliability of certain parameters, it should be noted that without a URL, these essential technical/scientific details to advance repository development cannot even be obtained. It should therefore be remembered that each type of operation brings possibilities and limits which must be taken into account in the development of a geological disposal programme. Investigations from the surface allow an overview of the geological environment being worked on, with some possibilities of detailed information from boreholes. The underground laboratory provides a much finer level of information with directly usable data for safety demonstrations. In any case, it will be essential that the reconnaissance and in situ studies do not induce any detriment to the performance of the disposal, particularly in the case of site-specific URLs directly related to the future disposal.

Table 4.1. Factors to consider in designing generic and site-specific URL programmes

Generic URL	Site-specific URL
Site selection denotes a site that is both relevant and scientifically interesting and able to be modelled. URL programme aims to develop and test methodologies with an emphasis on scientific development. Generic URL is an effective tool for demonstrating and communicating ideas and concepts. Although a URL site should not be considered for repository, such a decision is anticipated to be a rare occurrence and highly dependent on the types of activities that were conducted at the site.	Site selection denotes a future site for geological repository. URL programme must minimise perturbations to geosphere and requires rigorous quality assurance procedure. Invasive techniques may not be allowed. Scientific programme can be designed to address uncertainties surface-based investigations by collecting and specific data, at depth, relevant to detailed design and licensing safety assessment. Specific URL allows demonstration of repository concept at the repository scale as well as optimisation of disposal technology.

Table 4.2. Limitations of work in URLs

Generic URL	Site-specific URL
Transferability of results from generic to site-specific URLs or to proposed repository. Experiments with radionuclides may not be allowed, i.e. tests with radionuclides have only been carried out in several generic URLs (e.g. Grimsel, Mont Terri, Äspö, Asse). Boundary conditions can be complex especially when existing underground access is used (e.g. Grimsel).	Damage to the geosphere should be minimised with respect to negative impacts on the performance of the repository barriers. The comparative sizes of URL and actual repository may limit the heterogeneity of rock properties encountered during testing (e.g. volume of rock tested possibly may not be readily transferable to repository scale).

Strategies for URL development

In developing a URL, waste management programmes shall evaluate their research priorities. A purpose-built generic URL may or may not be required by a programme. Some countries may strategically develop one or more generic URLs using pre-existing underground facilities to investigate specific geological environments, and devise plans to develop a site-specific URL to achieve other site-specific details in a later stage. The following questions should be addressed when developing a URL.

How pressing is the need to dispose of waste?

Some countries may delay constructing a URL because final disposal of waste is not contemplated for several decades or more. In this case, it will be advantageous to follow developments in other countries, perhaps collaborating in programmes in foreign URLs, to benefit from as much knowledge and experience as possible when a national URL is needed. Even if the need is not pressing, a national generic URL may pay dividends in developing technical expertise and in building confidence in underground disposal.

If, on the other hand, disposal of waste is a pressing concern, the time might be right to proceed with either a URL aimed at specific potential geologic environments or a site-specific URL if a site has been selected.

Is a URL needed to develop and test a disposal concept?

Construction of, and experimentation within, a URL may be needed to develop, test, and demonstrate elements of a particular disposal concept before a decision can be made to construct a repository based on that concept. (Note: In France the development of a URL is required by law.)

Can desired information be obtained by co-operating in work performed in the URL of another country?

Most countries that currently have URLs offer the possibility for co-operative work with other countries. Provided that the information and experience are transferable from an existing URL to a particular repository concept (e.g. same type of geologic environment), performing work in an existing URL in another country may be a cost- and time-effective option during the period before a national URL is available.

Transfer of information as input to specific safety cases is an important element of confidence building (Mazurek*,* 2008). The basis of transferability as well as its limits needs to be elaborated and justified in each specific case. This basis is established by the characterisation, understanding and comparison of relevant host rock formation properties and/or the states of the system in the concerned sites. Transfer can also occur at different levels, depending on: i) the level of maturity of the safety case and ii) the quality of the analogy that can be made between the sites and formation concerned. In the early stages of a safety case development, information is transferred from other sites to complement the information gained from site characterisation and to obtain suitable and defendable data for a preliminary safety case. At this stage, the basis of transferability may not yet be very well established, and conservative assumptions may still be needed. In mature safety cases, the role of information transfer is smaller; supplementary data are needed to improve understanding of the process as well as to build confidence, such as by means of establishing empirical relationships which utilise information from diverse sites and settings.

Is going underground the most efficient way to satisfy research and testing needs?

Development of a repository requires research and testing that may be difficult without working in an underground environment. These capabilities may include specific technologies (e.g. for permeability testing or waste emplacement), understanding of processes, and experience in a variety of underground operations. While it can be argued that over time such essential information and experience will eventually be available from other URLs (unless none exist in the geologic environment of interest), which may benefit the small or less advanced programmes, the need for underground access and experience prior to repository construction will never disappear entirely. It is also reasonable to expect that in the licence application phase for the DGR the regulator will require site-specific information, and that this is only possible with direct access to the host rock.

Can an existing underground facility be adapted for generic URL work in a cost-effective manner?

Existing underground facilities (e.g. mines, tunnels) may provide an opportunity to develop techniques, equipment and/or expertise in a cost-effective manner that will be useful in future repository development. While an existing excavation may not serve the same range of functions as a new excavation, it may allow rapid progress in certain areas. At the start of studies on geological disposal, those carried out in the former Stripa Mine (Sweden) were particularly fruitful in this respect.

Is the overall waste disposal programme sufficiently advanced to provide continuity when the URL work under consideration is completed?

If too long a period of time elapses between the development of technology and expertise in a URL and opportunities for their continued application, valuable work and trained personnel can be lost. Thus, ideally, a continuous programme of work should be mapped from the first URL to a final repository before URL work begins.

What is the timing of site-specific URL development?

The establishment of a URL is generally part of the broader development agenda of the geological disposal programme for radioactive waste. The latter is a matter of decisions largely framed by political choices and therefore by socio-political conditions. In any case, a number of technical and administrative matters should be considered when deciding when to develop a site-specific URL. Sufficient time must be provided to acquire the necessary information and licensing before the construction and commissioning of the repository.

Are specific data needed that can only be obtained in a site-specific URL?

At some point, performance assessment modelling, engineering design and other aspects of a repository programme require detailed information that can only be obtained underground at the repository site. If a lack of such information is stalling the programme and all necessary preconditions have been met, building a site-specific URL is appropriate. This additional ("detailed") information may be more confirmatory and part of an initial repository construction. A site-specific URL would become part of a repository.

Have all necessary data been collected before the system is disturbed?

Excavation of a URL (or repository) may have significant, long-lasting effects on the surrounding geologic environment. Before excavation begins, baseline hydrogeologic conditions (e.g. hydraulic head, geochemical conditions) must be established and all experiments that can only be done in an undisturbed system must have been completed. Enough data should be collected from hydraulic tests and other sources to develop models that can be used to predict the effects of excavation.

Have all technical, logistical and regulatory preconditions been met?

One of the valuable aspects of URLs is that they can provide information on how excavation affects the properties of the geologic environment. This requires that monitoring systems be in place (and baseline conditions defined, as described above), that monitoring equipment be ready to be installed underground as soon as the excavations are open, and that personnel availability and other logistical details be worked out.

In addition to these technical and logistical preconditions, different aspects of the development (e.g. shaft construction, drift construction, ventilation systems) may have separate regulatory requirements and/or authorities. To avoid costly delays, all regulatory requirements should be discussed well in advance, so that they can be met on predictable schedules, consistent with the technical and logistical requirements of the work.

Is the programme ready to demonstrate full capability to build a repository?

One role a URL can fill is to demonstrate the capability to site, model, construct, operate and close a repository. Regulations in some countries may require construction of a URL before a repository can be built. Once a programme is ready to demonstrate the necessary capabilities, going underground may be highly appropriate.

Cost of URLs

Construction of URL facilities is both time-consuming and expensive, as it involves a vast amount of underground work. Underground construction of URLs requires special excavation techniques to limit disturbance to the rock with minimal stress and high-quality assurance procedures to achieve the high laboratory standards. Constructing a URL may easily cost around EUR 100 million and, once a URL is in operation, a significant portion of a disposal programme's budget may be allocated to support the underground research activities. Thus, the construction of a URL is not a decision taken lightly in any country. Indeed, the construction of a URL represents a tangible commitment to research and development in support of repository development. The fact that URLs are so widely implemented and used despite their cost is an indication of their value to national disposal programmes. An example is listed for reference.

Costs for the Bure URL (France) as of 2010:

- Construction cost: EUR 280 M.
- Operational R&D programme including exploitation costs: around EUR 60 M/year.

5. Lessons learnt from URLs

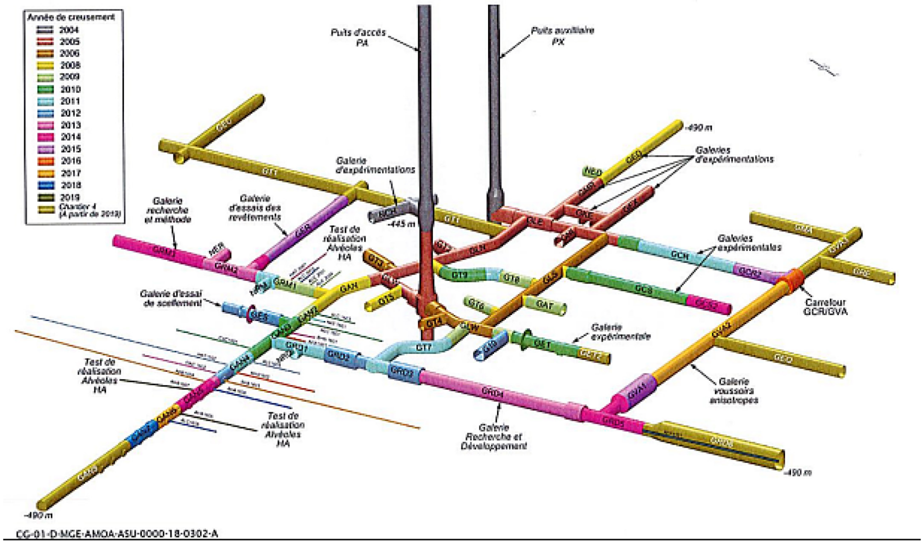
Work in the Asse Mine in Germany – the first generic URL – began in 1965; the first purpose-built generic URL was created in 1984 in Canada; and the first site-specific URL was created in 1980 in the Konrad mine in Germany. Overall, the accumulated experience of all existing URLs exceeds 250 years of operation. Among the 11 NEA member countries that have developed URLs (as shown in Tables 2.1-2.3), many of them have now gained experience in developing both generic and site-specific URLs.

Since the late 1990s, the number of site-specific facilities has increased and a few new, purpose-built URLs have come into operation. These include:

- The Bure URL, located in Meuse/Haute-Marne, France (Figure 5.1), a site-specific URL purposely built to study a 165 million-year-old clay rock. In October 2004, Andra started its first experimental programme aimed at qualifying the indurated clay rock, in situ at 495 m of depth, as a favourable host rock for the long-term containment of HLW. The first experiment goals were to characterise the intrinsic properties of the clay such as its very low permeability, sorption potential and thermal conductivity, and to assess the behaviour of the rock mass to digging (EDZ, self-healing properties, etc.). The conclusions of this first experimental programme were used to support the feasibility study of a DGR project in clay and assess its long-term safety performances as reported into the Dossier 2005. After two years of expansion of the URL, Andra launched the second phase of its R&D programme with the objective of studying the impact of the disturbance brought by HLW to the favourable properties of the clay rock. Experiments on coupling processes (thermal-mechanical-hydro-chemical) and material behaviour and testing on construction technologies were implemented. Since 2016, with the third stage of development of the URL, new experiments were added to assess the robustness and maturity of the Cigéo design and constructability. Finally, after nearly 20 years of mechanical, hydraulic, geochemical and thermal characterisation of the host rock from the URL, 15 years of experience feedback for the construction of large-scale structures for the disposal of ILW, and 12 years of testing for the construction of high-level waste disposal cells and equipment, Andra submitted the licence application for the construction of the Cigéo geological disposal in early 2023.
- The KAERI Underground Research Tunnel (KURT), located in Yusung Gu, Korea (Figure 5.2), is a purpose-built generic URL completed in 2006 with two research tunnels designed for various in situ experiments of granitic rock.
- The ONKALO facility in Finland (Figure 5.3) is another site-specific, purpose-built URL specifically designed in 2003 to study the granite bedrock and groundwater conditions of the nearby Olkiluoto underground storage facility.

Several countries do not operate their own URLs (Czechia, the Netherlands, Spain and the United Kingdom), but have co-operated or are co-operating on research in other national URLs. Thus, almost all of the NEA member countries with geologic disposal programmes are engaged in research at URLs although their repository programmes are at different stages of development.

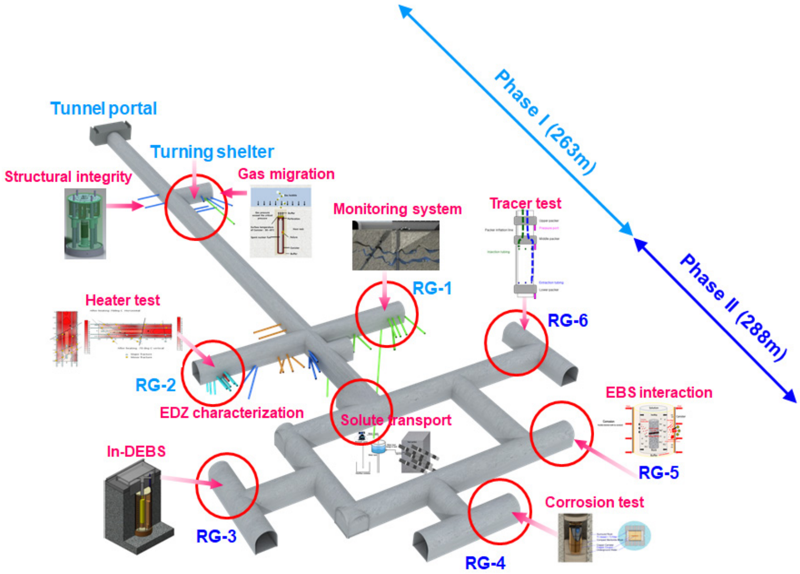
Figure 5.1. General layout of Andra's URL at Bure



Source: Andra, 2024.

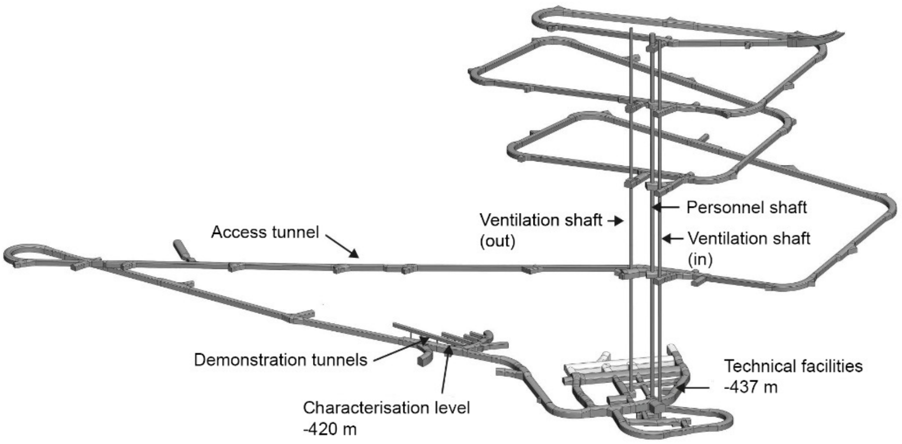
Note: The underground installations of the Bure URL include two 500-m deep shafts measuring 5 and 4 m in diameter, respectively, one 40-m long experimental drift located in the upper part of the argillite formation at 445 m, and a 485-m long drift network within the core of the argillite formation at 490 m.

Figure 5.2. KURT URL



Source: KURT, 2024.

Figure 5.3. ONKALO



Source: Posiva, 2024.

The evolution of work performed in URLs

The types and amounts of work performed in URLs have evolved with time. When work in the first URLs began more than 40 years ago, much of the sophisticated technology required for radioactive waste repositories was in its infancy. The priorities were the development of equipment and testing methodologies as well as basic engineering feasibility studies and the collection of fundamental geologic data. Those types of activities are currently receiving decreasing emphasis because of the information now available. Efforts are directed towards more integrated (and more complex) projects with two main characteristics:

- Field experiments under repository-relevant boundary conditions, e.g. large-scale, long-term, realistic hydrogeological conditions. Examples include the development and testing of engineered barrier components under representative repository conditions and large-scale development and testing of waste emplacement technology.
- Projects addressing the implementation of a geological repository (e.g. engineering feasibility, operational aspects, closure, monitoring and possible effects of repository construction on the surrounding rock). Examples of studies include the development and testing of long-term monitoring approaches and technologies; the demonstration and testing of waste retrievability and understanding the constraints on transfer of information from a URL to a potential repository sited in the same or a similar host rock formation.

The work carried out in URLs has also evolved in parallel with the needs and results of iterative safety assessment studies, so that it now focuses on reducing uncertainties and increasing confidence in the safety case. For example, tests may be carried out to distinguish between alternative conceptual models or to develop improved scientific understanding of specific processes. Emphasis is also being increased on full-scale demonstration-type experiments related to engineered barrier systems and on long-term and large-scale tracer experiments.

Table 5.1. Technical information obtained from URLs

Objectives	Examples
Develop methods, equipment and experience for underground characterisation and monitoring techniques.	Ventilation experiment, cross-hole hydraulic and seismic tests, borehole radar and validation drift experiments at Stripa. Extensometer development at AECL URL. Deep Doorstopper Gauge System (DDGS) developed at AECL URL to measure in situ stress during overcoring drilling. Development of equipment and procedures for brine permeability tests in halite at WIPP. Brine migration test at Asse. Development of pressure monitoring devices at Bure as well as methodologies for Hydro and gas permeability testing specific equipment for interaction tests between disposal materials and claystone at Bure. Development of geophysical methods for fracture detection (from the surface and from the galleries) at Tournemire. Development of a new piezometer at Mont Terri (low hydraulic conductivity, very low free water content). Development of fibre optic technologies for data transmission and temperature measurements at Bure. Development of on line porewater sampling and chemical analysis devices (Ionic chromatographer, gas spectrometers…) at Bure. Development of ground penetrating radar tools which increase the depth of penetration in rock salt up to several hundred metres; increase of spatial resolution and direction sensitivity at Gorleben. Ultrasonic in situ methods were applied for the determination of elastic parameters at Asse and Gorleben. Development of techniques for assessing earthquake impact on the deep geological environment at Kamaishi, Mizunami and Horonobe. Development programme of hydraulic and hydro-chemical monitoring (Äspö). Development of multidisciplinary site descriptive modelling (Äspö). Development of a test facility for quality control of the accuracy of borehole deviation equipment (Äspö). Development of mapping systems for tunnels and deposition holes based on photogrammetry (Äspö). Development of method for groundwater sampling for analyses of dissolved gas and isotopes in gases (Äspö). Development of site investigation programme incl methods, QA/QC, equipment and modelling (Äspö). Development and implementation of data management system (databases, software and codes) (Äspö).
Determine reliability of surface-based methods of site characterisation.	Comparison of permeability test results from deep boreholes with in situ permeability tests at WIPP. Comparison of pre-excavation predictions to properties found in tunnels at Äspö, Mizunami and Horonobe. Comparison of 3-D seismic images and core survey from directional drilling at Bure. Development of 3D seismic analysis techniques to provide evaluation of poro physical parameters of the clay-rock formation as well as overlying limestones formations at Bure.

Table 5.1. Technical information obtained from URLs (cont.)

Objectives	Examples
Provide data for repository design and performance assessment, which allows strategic site exploration to be carried out as more specific information is acquired from the URL.	Fracture mapping and hydraulic measurements to select locations for full-scale deposition holes in Olkiluoto Research Tunnel. EDZ Investigation techniques and analysis at Bure. Thermo-hydro-mechanical experiments at Mont Terri and Bure laboratories. Application of geophysical methods at Grimsel Test Site, Tournemire, Stripa and Äspö.
Testing and development of conceptual and numerical models of processes potentially relevant to radionuclide transport through rock.	Radionuclide retardation and migration projects at Grimsel Test Site (DRR, CFM, LTD). In situ study on natural uranium migration in the reducing environment at Tono. Unsaturated zone transport tests at Yucca Mountain. Solute transport and diffusion experiments at AECL URL, Kamaishi, Bure and Mont-Terri. Water permeability tests at Bure for in various phenomenological contexts. Gas-threshold-pressure tests at WIPP, Bure and Mont Terri. Tracer retention programme at Äspö. Radionuclide and gas migration experiments at HADES. Development of methodology for evaluating the contribution of the different transfer mechanisms (e.g. osmosis and thermal osmosis, advection vs. diffusion). Development of numerical model and evaluation of transport mechanism based on tracer-profile data obtained from argillaceous rocks at nine sites in central Europe (CLAYTRAC).
Develop methods, equipment and experience in repository construction, operation and closure, and in waste retrieval: (i) Quantification of impacts of excavation on local system.	Excavation-damaged zone experiments at Äspö, Grimsel Test Site, AECL URL, Tono, Kamaishi, Horonobe, Mont Terri and WIPP. Disturbed zone studies around blasted tunnel and drilled disposal holes in Olkiluoto Research Tunnel and AECL URL. Studies of the self-sealing behaviour of clay host rock in the excavation disturbed zone (EDZ) at HADES and in Bure (CDZ experiment). Joint geological survey of drift and resin impregnated cores with EDZ permeability tests at Bure. Study on changes in geochemical conditions in tunnel near-field environments at Tono, Kamaishi, Mizunami and Horonobe.

Table 5.1. Technical information obtained from URLs (cont.)

Objectives	Examples
(ii) Further development and testing of excavation techniques.	Excavation techniques in plastic clays at HADES: • demonstration of technical feasibility of drilling galleries, using an industrial tunnelling machine; • demonstration of technical feasibility of a crossing between galleries; • follow-up of Boom clay behaviour during excavation. Development of a new method to install the lining behind a micro-tunnelling machine at HADES. Comparison of tunnel mechanical excavation and blast excavation techniques at Äspö, Tono and Grimsel Test Site. Studies of the performance of disposal technologies at Olkiluoto. Development of careful drill and blast excavation techniques at AECL URL, Kamaishi and Horonobe. Demonstration of microtunnel drilling and lining for vitrified waste at Bure. Packer tests for excavation-damaged zone measurements at Morsleben*, Bure and Tono.
(iii) Simulation of effects caused by emplacement of radioactive waste (heat, radiation, nuclide release, mechanical impact, gas release).	Study of the effect of heat and radiation on clay at HADES: • small-scale heater tests; • large-scale heater test with a heated section of 35 m, over a period of 10 years. Thermal simulation of drift emplacement at Asse. Heater tests at Stripa, Yucca Mountain, WIPP, Asse, Mont Terri and Grimsel Test Site. Large heater tests experiments at Bure simulating the thermal load of a high-level waste canister Thermal-structural interactions tests at WIPP. Thermal-mechanical-hydraulic tests at AECL URL and Bure.
(iv) Studies of material interactions in repository environment such as experiments related to long-term processes, post-operational phases, corrosion, geo-mechanical stability, etc.	Corrosion tests and gas experiment at HADES. Stability of the glass matrix (vitrified waste) in contact with Boom clay at HADES. Coupled thermal-hydraulic-mechanical processes test at Kamaishi. Materials interface interactions tests at WIPP and Bure. Cement/glass/iron/bentonite interactions at Bure in various phenomenological situations. Long-term Cement Studies (LCS) at Grimsel Test Site. Backfill and material behaviour at Asse*. Concrete/rock interactions and effects on the rock properties at Tournemire (contact duration up to 125 years, age of the tunnel). Demonstration of the feasibility of low-alkaline concrete for tunnel support and sealing at Horonobe. Demonstration of the feasibility of low-alkaline shotcrete plug at Grimsel.

Table 5.1. Technical information obtained from URLs (cont.)

Objectives	Examples
(v) Demonstration of engineered barrier systems (feasibility).	Borehole sealing and buffer mass tests at Stripa. Full-scale engineered barriers experiments (FEBEX) at Grimsel Test Site. Development of borehole seals for HLW canisters at Asse. Full-scale tunnel and shaft sealing tests at AECL URL. Development of Thermal-Hydraulic-Mechanical (THM) instrumentation, monitoring systems, and a set of parameters for post-closure monitoring of full-scale seals at AECL URL. Gained experience in construction of full-scale seals in water bearing aquifer and monitoring of their performance and evolution for over 15 years at the AECL URL. Gas Permeable Seal Test (GAST) at Grimsel Test Site. Small-scale seal performance tests at WIPP. Repository sealing experiments at HADES: seal test for horizontal drift, borehole seal test and shaft seal test. Repository sealing experiments at Bure and at surface at real scale (FSC experiment). SEALEX programme at Tournemire: performance tests of repository seals. Test of geotechnical barriers (dams) (Asse* and Morsleben*). Investigation of crushed salt backfill compaction behaviour (Asse). Backfill experiments at Bure Engineered barrier experiment (EB) at Mont Terri.
(vi) Demonstration of emplacement techniques and waste retrieval.	ESDRED programme (several). Äspö Retrieval Test.
(vii) Demonstration of durable and non-intrusive monitoring techniques.	ESDRED at Mont Terri, Project TEM (Grimsel Test Site) and EC Project MoDeRn (Bure, Grimsel Test Site, HADES).

*It should be pointed out that some of the tests and research reported at Asse as well as at Morsleben were not carried out as part of works in URL, but rather in response to needs for safety and operation of the works.

Examples of work performed in URLs

Examples of work that has been performed at URLs are summarised in Table 5.1 and the general types of research work/studies are discussed below.

Develop methods, equipment and experience for underground characterisation and monitoring techniques

Characterisation of the underground environment from within a URL requires equipment and procedures that are different from those commonly used for surface-based investigations or for conventional mining. Each repository programme also has its own unique concerns that necessitate some degree of invention and innovation. Figure 5.4 shows the brine availability test in salt in the WIPP facilities (NM, United States). URLs provide the opportunity to develop and test the tools that will be needed for characterisation of a repository and, just as importantly, allow personnel to gain proficiency with those tools and form effective teams. URLs also provide the opportunity to develop and test whatever monitoring systems might be required around and in a repository.

Another important aspect of developing capability and experience in underground characterisation is the quality management (QM) system which will be developed and tested at the same time. Tested and effective QM procedures are critical underpinnings of a licence application for a repository.

URLs are also excellent tools for providing specific training to staff who will be responsible for the safe management of repository operations. Such a notion can be illustrated by the IAEA Underground Research Facility (URF) network, which efficiently utilises the nationally developed URLs, operated by network partners, to provide training and demonstration of waste disposal technologies to the network participants. More information regarding the IAEA URF network can be found at www.iaea.org/OurWork/ST/NE/NEFW/WTS-Networks/URF/urffiles/URF-Brochure.pdf .

Figure 5.4. Salt experiments in the WIPP facility (NM, United States)

Ongoing test at the WIPP facility, the brine availability test in salt (BATS)

Source: WIPP, 2024.

Left: A picture of overcoring operations. 12” diameter horizontal core was being collected in the background from heated and cement seal exposure tests as part of the BATS 1 heated array. The WIPP test co-ordination office is marking and logging the core on a pallet in the foreground.

Middle: A picture of the maintenance of the BATS 1 heater and packer in the WIPP underground test areas in bed salt for the heated BATS experiment. Arrangements for instrumentation and wiring as part of the BATS 1 heated array.

Right: Instrumentation and wiring coming out of the boreholes in the BATS1 heated array. The sensors, cables, pre-amplifies and tubing are associated with thermocouples, electrical resistivity tomography, fibre optics, acoustic emissions, and gas flow in/out.

Determine reliability of surface-based methods of site characterisation

Before construction of a URL begins, surface-based site-characterisation methods provide data that are used to first develop a conceptual model and, second, a numerical model(s) of the site. Subsequent excavation of the URL provides the opportunity to verify predictions made on the basis of those models, such as the occurrence of fracture zones. Linkages can also be developed between the characterisation parameters measured from the surface (e.g. in boreholes or surface-based geophysical surveys) with those measured from within the URL. In this way, those surface-based methods and/or models that are successful (or useful) in predicting underground conditions can be differentiated from those that are not and carried forward into the repository siting and characterisation programme. The ability to predict subsurface conditions accurately is one key in demonstrating the feasibility of finding an acceptable repository site.

Provide data for repository design and performance assessment

Whether generic or site-specific, a URL allows the collection of characterisation data that complement the data obtained from surface-based investigations and laboratory experiments. These data may be collected at any depth along the access tunnels and shafts, allowing much more than characterisation of only the potential repository horizon. This also includes collecting (undisturbed) samples for laboratory work that otherwise could not be sampled. These data can be used to develop and test models of repository and geosphere performance, allowing an understanding to be developed of the sensitivity of various performance measures to variations in measured characterisation parameter values. The URL data have the added value of better reflecting the conditions of the actual repository (i.e. near-field) conditions than borehole data. Experiments can be conducted over larger volumes of geological environment within a URL than in a borehole, allow development of upscaling rules, and can be better focused on characterising heterogeneity and reducing remaining uncertainties. In some formations, sampling of pore water can only be performed effectively from within a URL.

In the case of a site-specific URL, the better understanding of existing lithological variations, important structures and other heterogeneity that can be obtained underground is also essential to the final design of the repository. In addition, some forms of monitoring before repository construction can only be performed from within a site-specific URL.

Testing and further development of conceptual and numerical models

The URL provides an environment for the testing and further development of models at various levels of detail. This includes models to be used in repository design and optimisation of layout, such as models of geo-mechanical and thermal response and models of the hydrogeologic regime, as well as models to be used in safety assessment such as models of solute and radionuclide transport through rock.

Develop methods, equipment and experience in repository construction, operation and closure, and in waste retrieval

A URL allows development, demonstration and quality management of technologies for repository construction, repository operation, waste emplacement with engineered barriers, and backfilling and sealing under realistic conditions. For example, design and construction of any repository will have to be adapted to the specific heterogeneities encountered at a site. Construction of a URL allows determination of the feasibility of the methods proposed for that adaptation. It also allows testing of the design-as-you-go concept as proposed by e.g. SKB and Posiva, in which the exact locations of tunnels and waste canisters are not determined until enough rock has been explored to select optimal locations. If the potential for reversibility of the disposal decision is an element of the overall disposal programme, a URL also offers the opportunity to develop, test and demonstrate equipment and methodologies for waste retrieval and removal.

A URL also allows for study of the interactions of materials that might be used in repository construction and waste packaging with engineered barriers and a geological environment that is representative of in situ conditions that include different possible thermal regimes and use technological demonstrators. The geo-mechanical effects of different excavation methods can also be evaluated within a URL. At the same time that these evaluations and demonstrations are performed, the QM procedures that will need to be in place during development and operation of a repository can be developed and tested. Personnel will also gain valuable experience and confidence during all of these activities.

All the experiments and surveys in a URL can support the development of the repository monitoring, for example by:

- proposing a viable monitoring strategy for the disposal management and the safety assessment;
- developing innovative tools;
- developing more robust gauges for disposal cell environment and/or increasing their reliability over several decades to inform reversibility management.

To assist future strategic URL activity planning, Boxes 5.1 and 5.2 describe the lessons learnt from AECL’s URL (generic) in Canada and from Onkalo (site-specific URL) in Finland, respectively.

Box 5.1. Lessons learnt from a generic URL – AECL's Underground Research Laboratory (Canada)

Active from 1982 until 2010, when it was permanently closed, Atomic Energy of Canada's Underground Research Laboratory (URL) was the first of the purpose-built URLs. Constructed in a previously undisturbed site, the URL allowed for investigation of the option of deep geological disposal of used nuclear fuel in a granitic host rock, though much of the work conducted was applicable to repositories in any host rock type.

While the URL was closed on 2010, several activities continued beyond that date. Post-closure monitoring of surface 22 boreholes continued until 2014. The Enhanced Sealing Project (ESP), the final R&D experiment at the URL, monitoring the full-scale shaft seal at the URL has been continuing for over 16 years as of 2023 (Priyanto, 2023). The URL consisted of two working levels at ~240-m and ~420-m depths, two drilling stations at ~130-m and ~300-m depths, and two vertical shafts as shown in Figure 5.5. The photographs of the URL during its operation are shown in Figure 5.6.

The URL allowed the full effects of underground excavation, construction, simulated container installations and ultimately facility closure to be evaluated. The site was extensively characterised via exploration and monitoring boreholes and a variety of geophysical and other tools prior to the initiation of excavation, providing a measure of the undisturbed, baseline conditions. The effects of subsequently installed experiments and the presence of underground openings on the regional hydrogeology were monitored throughout the URL's operation. As part of the URL closure, a shaft seal similar to what may be used in an actual repository was installed and continues to be monitored, together with the recovery of the site's groundwater conditions, providing a full start-to-finish record of site conditions.

The programme of study at the URL is formulated along three broad topic areas listed below (Baumgartner, 2007):

- study of site characterisation or long-term geologic monitoring methodologies;
- study of solute transport through fractured and unfractured crystalline rock;
- study in support of the engineering design of repository sealing systems.

Below are listed the key lessons learnt and technologies developed over the course of the URL's design, construction, operation of the experiments and facility closure. More detailed URL experiments and studies can be found at the AECL web link (as listed in Appendix A):

- The URL was a vital part in developing technical and regulatory confidence in the Canadian repository concept and construction feasibility.
- A URL was needed to develop specialised knowledge of system behaviour and technology together with training personnel who will be needed for repository design and construction.
- The URL provided a site where improvements to the efficiency of vertical shaft excavation in hard-rock environments were developed.
- Grouting materials and techniques were needed in order to seal sparsely fractured rock. This resulted in development of micro-fine grouts and grouting techniques that were subsequently applied by a variety of mining and geotechnical projects.

Box 5.1. Lessons learnt from a generic URL – AECL's Underground Research Laboratory (Canada) (cont.)

- There was a need to minimise repository influence on the chemistry of the surrounding hydrological environment (and also containers and sealing materials). This drove development and testing of low-heat, low-pH, high performance concrete (and grouting) materials in a geological environment. This technology has subsequently been further developed and is being applied in a variety of nuclear and non-nuclear applications.
- Excavation damaged zone (EDZ) associated with excavation (and subsequent geo-mechanical evolution) is a critical consideration. The EDZ can result in preferential flow of water past the backfill or plugs in a tunnel if it is not correctly intersected. The experiments at the URL provided a great deal of knowledge on the character and development of the EDZ.
- Excavation of stable openings with a limited disturbed rock zone under high differential stress conditions is a major technical challenge. A series of studies monitored the effects of excavation on the surrounding rock and techniques were developed to identify the extent of the subsequently developed EDZ, showing that it was possible to excavate openings and tunnels and subsequently effectively seal them in high-stress environments.
- Careful blasting techniques coupled with numerical modelling of excavation geometries demonstrated it was possible to limit the EDZ under high differential stress conditions.
- The interaction between a heat-generating source (container simulation), the engineered barriers surrounding it and the surrounding geosphere were studied. These demonstrated strong thermal, hydrological, mechanical, chemical (THMC) and biological linkages and the importance of understanding how the components interact.
- Accurate monitoring of conditions at the URL allowed the development and testing of numerical models (geosphere, performance assessment).
- Rock samples from depth are altered when they are removed from in situ stress conditions, which made laboratory measured parameters have limited accuracy. Thus, a Deep Doorstopper Gauge System (DDGS) was developed at the URL to measure in situ stress during overcoring drilling.
- Parameters such as diffusion are more accurately determined in situ under ambient stress conditions than in the laboratory, where rock samples have been disturbed.
- The evolution and performance of sealing system components developed from laboratory tests and simulations need to be tested at full scale in a representative environment relevant to a repository in order to evaluate their THM evolution and demonstrate their constructability using the existing construction technology.

From the data developed from monitoring of the various experiments at the URL, it has been possible to develop and test numerical models, providing for a greater confidence in our ability to predict both short- and longer-term evolution of a repository for used nuclear fuel.

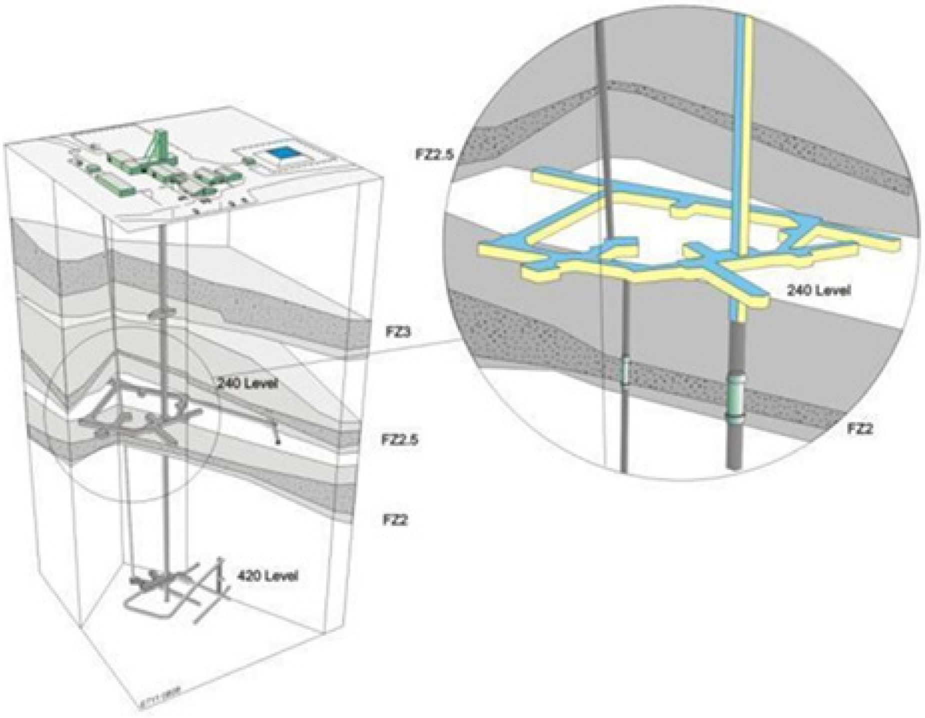
Many of the experiments, programmes and studies performed at the URL involved co-operative projects with organisations from Japan, Finland, France, Korea, Sweden and the United States. Associated with many of these physical activities were numerical modelling exercises intended to help develop simulation tools for use in engineering design and/or performance assessment.

Box 5.1. Lessons learnt from a generic URL – AECL’s Underground Research Laboratory (Canada) (cont.)

The AECL URL provided a facility where it was possible to develop and test technologies and approaches that can ultimately be applied to construction and operation of a repository for permanent disposal of used nuclear fuel in Canada. It also provided a facility where issues identified as being potentially significant to repository safety could be addressed in a timely manner under field conditions.

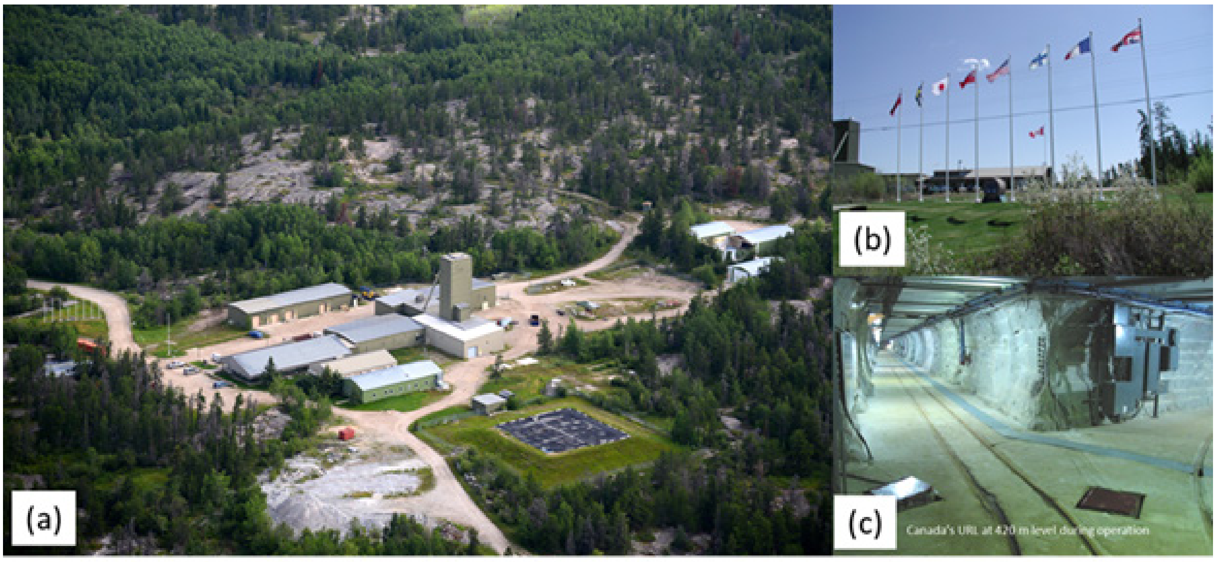
Lessons learnt from the AECL URL have been published by Chandler (2003), Baumgartner and Thompson (2007), Thompson and Priyanto (2014), and Priyanto et al. (2019). Those reports include technical and non-technical lessons learnt and discuss several major large-scale experiments. They include: Isothermal Test; Buffer Container Experiment; Quarried block radionuclide migration; Solute transport in highly fractured rock; Solute transport in moderately fractured rock; Mine-by; Excavation stability study; Isothermal test; Solute transport Excavation Damage Zone; Connected permeability tests; Heated Failure Tests; Tunnel sealing experiment; and Enhanced Sealing Project (ESP). The technical programme at the URL was instrumental in developing the Environmental Impact Statement (EIS) on the Concept for Disposal of Canada’s Nuclear Fuel Waste (1994). Founded in 2008 (Dixon et al., 2008), the ESP is still ongoing as of 2023 (Priyanto, 2023) to monitor the full-scale shaft seal. This demonstrates that collaboration between multiple organisations from different countries has enabled the creation of unique 45+ years of database representing a life cycle of a URL from preconstruction and operation to post-closure phases.

Figure 5.5. AECL URL underground facilities and full-scale seals installed at the URL



Source: AECL, 2024.

Figure 5.6. Photographs of AECL URL during its operation (a) aerial view; (b) collection of flags representing the AECL URL partners; (c) view of 420 level



Box 5.2. Lessons learnt from a site-specific URL – ONKALO Underground Rock Characterisation Facility (Finland)

The deep geological repository facility for used nuclear fuel in Finland, Olkiluoto, has progressed to its final "site confirmation" stage which includes the construction of an underground rock characterisation facility. This underground characterisation facility, known as ONKALO, has the objectives to confirm the suitability of the Olkiluoto bedrock for hosting a geological repository, to finalise the detailed design and construction of the repository and to assess the long-term safety of the facility. With the characterisation facility, ONKALO, which is to be located at the selected site, Olkiluoto, technology research and studies can be performed under actual repository conditions. In addition to its research function, ONKALO has also been designed to serve as an access route to the future repository. The construction of ONKALO began in 2004 and was completed in 2014. Site investigations have been carried out since the start of construction in conjunction with excavation.

Lessons learnt from ONKALO thus far contribute to the areas listed below:

- long-term safety;
- operational safety;
- design and construction;
- contracting and project management;
- site characterisation;
- quality management;
- quality control.

Source: AECL, 2024.

Box 5.3. A programme in the URL directly supporting the DGR development

The Bure URL (France)

Following a parliamentary process (1991) and a call for volunteers, the construction of the URL on the Bure site was authorised at the end of 1999. The digging of the URL began and reached the target clay-rock formation of the Callovo-Oxfordian in 2004. On the basis of the first scientific results, the site was chosen by Parliament to host the Cigéo disposal project for high-level waste and intermediate-level, long-lived waste (Jacques Delay et al.).

Four stages of scientific and technological experimental programmes have been implemented:

Stage 1: 1999-2005

The first task assigned to the URL was to confirm the containment capability (diffusion and retention of radionuclides) of the host clay-rock formation through its hydrodynamic properties and the chemical composition of the pore water, which could only be sampled directly from the URL. The other key objective was to confirm that the construction would be possible in technically and financially acceptable conditions. An additional requirement from the regulator was to study and define a sealing concept for the disposal drift final closure.

Stage 2: 2006-2010

Following the 2006 Planning Act, stage 2 aimed at providing the scientific and technical basis for safety and design options. Several excavation and support techniques were tested as well as various types of compressible materials for the drift support in order to accommodate drift convergence. The first micro tunneling machine for excavation of HLW disposal vaults was also tested (Figure 5.7). Scientific experiments were focused on thermal, hydrological, mechanical and chemical (THMC) coupled processes and on gas migration processes. Interaction between materials (cement/iron /glass) and clay rock were also investigated and experiments launched during this stage.

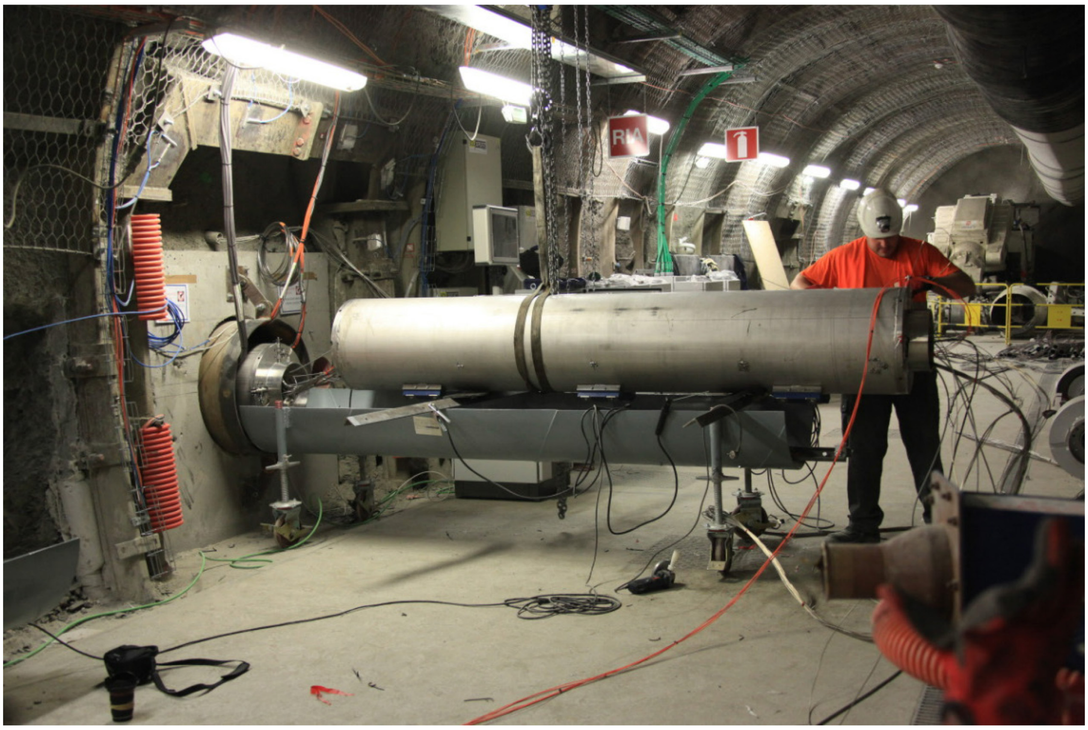
Stage 3: 2010-2018

During stage 3, the objective was to provide scientific support to the 2016 Safety Option Report for the Cigéo disposal facility. Many large experiments were also launched during this stage. The main experiments were related to the construction of drift built with a tunnel boring machine (TBM) that included a segment erector. Soft-supported drifts and rigid-supported drifts were drilled and equipped with different types of supports and liners. A 9 m diameter drift foreshadowing a ILW vault was built to accommodate TBM assembly. A large-scale experiment dealing with a sealing component concept started after 5 years of design and many preparatory tests.

Stage 4: 2019-2025

The fourth stage of development aims at testing optimisation options before the start of the disposal construction. The main objectives of the work are linked to specifying and assessing the detailed construction requirements for each disposal component (shafts and drifts, disposal vaults, seals). The technical programme comprises large-scale experiments dealing with dismantling techniques such as the removal of segment rings. The most ambitious experiment is the construction of an ILW cell at real diameter but reduced length, including its equipment.

Figure 5.7. Illustration of a temperature test in a HL vitrified waste disposal cell – Bure (France)



Source: Andra, 2024.

6. International co-operation discussion

The costs involved in the development and operation of a URL, and the possibility of sharing existing knowledge and experience, can make international co-operation in underground studies advantageous. International co-operation promotes exchanges of ideas, creativity and better-quality research as well as peer review. The collective demands of several organisations reinforce the meeting of milestones and adhering to budgets. Countries involved in international URL co-operation projects are listed in Tables 2.1 to 2.3. The benefits of international co-operation in URLs include:

Expanded talent pool

International co-operation projects allow qualified scientists and engineers, in terms of both ability and experience, from numerous countries to work together. This expansion of the talent pool allows for cross-fertilisation of ideas and more rapid advancement of research and confidence building.

Expanded contacts and knowledge transfer

A direct benefit of the trend towards collaborative international projects in URLs is the development of international and interdisciplinary contacts and knowledge transfer that may be valuable in other aspects of repository development, such as site characterisation and performance assessment.

Cost-effective research

All parties to international co-operation projects gain by obtaining research results that they do not have to pay for fully themselves. The host country of the URL benefits from the results of the efforts of other participants, which can be not only of generic value but also valuable site-specific data from having studies conducted in their own URL. The non-host countries can learn from the example of others, gain practical experience on a generic basis, and develop their technical and managerial expertise, all of which should make their own repository programmes more efficient when they reach the URL stage. International co-operation in specific experiments performed in URLs, such as tests of seal concepts in crystalline rock, also may avoid costly duplication of complex developments in other countries.

International recognition and increased confidence

Opening a URL to international co-operation boosts the international recognition and credibility of the host programme. This promotes confidence in the host programme by demonstrating openness to outside experts and promoting peer review and dissemination of results to a broader community. These initiatives indicate to the public, technical experts and other stakeholders that there is international agreement on the important issues and approaches to addressing them.

7. Conclusions

Development of an underground research laboratory and/or participation in international underground R&D activities is useful and a necessary step towards developing a disposal programme of radioactive waste in deep geologic formations. URLs provide important technical knowledge and increase confidence in the process of facility siting and design, underlying engineering support, and the evaluation of safety. Certain types of information and experience necessary for characterisation, construction, operation and closure of a geologic repository can only be obtained through access to the underground environment. Similarly, confidence in the facility design, the suitability of potential geologic environments and the technical feasibility can only be gained through underground verification and demonstration. All of these factors are important in building the safety case for a repository and the many existing and successfully operating URLs provide the valuable information.

URLs may be either at sites where no waste will ever be disposed of and only research will be performed, or site-specific, in which case the scientific investigations and other activities are intended to be the initial stage of or precursors to repository construction and operation. URLs offer an excellent opportunity to integrate multiple disciplines (e.g. geology, hydrology, engineering), build technical teams and gain practical experience that will be invaluable in future development of a repository. URLs also offer an unparalleled opportunity to demonstrate the disposal concept and technical feasibility of a repository programme, and instil confidence in the wide range of stakeholders that a repository programme has a valid basis and is being pursued in a responsible manner by a capable implementer. From the regulatory perspective, a URL allows regulators to develop their own expertise. URLs supply information that is of direct relevance to the regulatory authorities in their assessment of the long-term safety general feasibility of the proposed disposal concept.

URLs are useful in attracting international co-operation. This provides a wider talent pool to draw upon, expanded contacts and know-how transfer that can be useful in other areas of repository development. It is a cost-effective way to perform experiments, as expenses are shared among nations, and provides wider international and technical recognition and increased confidence both in the waste management organisation and in the feasibility of geologic disposal.

The work performed in URLs has evolved with time. Development of equipment and testing methodologies and experiments to enhance understanding of key processes, as well as basic engineering feasibility studies and collection of fundamental geologic data, were priorities in the first URLs. Efforts are now directed more towards large-scale, realistic, integrated experiments in which a number of interacting components and/or processes are simultaneously studied. The confidence-building role of URLs is also gaining in importance, as well as its training capacity for the personnel who will succeed each other over time for the construction and operation of the geological repository. Large-scale, long-term, integrated studies play a key role in raising technical and public confidence. Full- or large-scale experiments performed to date have highlighted potential optimisation areas. It is anticipated that URLs will continue playing an important role in repository operations, even after repository closure.

In the field of geological disposal of radioactive waste, the programmes are constantly evolving. In recent years, there have been major advances in particular with the start of construction of the Onkalo underground repository in Finland, the licence for the disposal of spent fuel in Forsmark (Sweden), and the licence application for Cigéo in France. Major progress has also been made with the identification of candidate sites in Canada and Switzerland. In Japan, the literature survey, as the first stage of the siting process, has been initiated at two municipalities, while the government is considering strengthening its efforts to implement the survey in as many areas as possible.

These developments have been made possible thanks to the large amount of work undertaken in research, engineering and the approaches to the safety assessment, which provide a basis to develop a safety case of underground repositories. Many studies and research efforts have been undertaken at URLs built for this purpose. Whether generic or specific to a site, they provide the knowledge needed to understand the local functioning of the geological environment. They also make it possible to test the methods of construction and closure of the disposal structures, as well as the equipment that will be necessary for their operation and for the necessary monitoring.

The key point in obtaining a licence for the creation of a deep geological repository is to demonstrate that its safety can be ensured during construction and operation as well as after closure.

Regarding the construction and operation phases, the demonstration is often based on experience available in both the nuclear and mining sectors. However, it is necessary to demonstrate their implementation under the conditions required for the geological disposal of radioactive waste, which is practised in underground laboratories.

The long-term safety demonstration requires not only understanding of the functioning of the geological environment, but also an evaluation of its behaviour in the presence of the engineered barriers and radioactive waste. It is essential to demonstrate, by developing a safety case, that the geological disposal system, i.e. the assembly containing the waste packages, the engineered structures and the geological environment, will be able to confine and retain the radionuclides for as long as they present an unacceptable risk for the environment and for humans. Given the time scales involved, demonstration is hardly possible through experimentation alone. It is necessary to resort to digital simulations for the safety assessment, the quality of which will depend heavily on the physical understanding of the phenomena likely to occur in the repository and their representation by modelling.

To implement a reliable safety assessment that can provide confidence in a safety assessment, it is therefore necessary to start with high quality science and engineering, which is the goal of research at URLs.

Since the report on URLs published in 2013 (NEA, 2013), many advances have been made in the URL projects, with plans to construct a new URL in many countries. The URLs share much more extensive functions than those mentioned before, of research and technology studies. Given the time constants for the various projects, URLs make it possible to train the teams that will have to successively build and operate the geological repository over decades or centuries. The URLs also make it possible to illustrate to stakeholders as well as to the general public what a geological repository will be, to provide all the explanations on the research and technological developments that are practised there, and therefore to increase overall confidence in the geological disposal. Certain tests will benefit from being maintained in a URL, in particular those requiring measurement durations or dimensions that would not be compatible with the life of a repository, whether in the construction phase or in the operating phase. The URL is also a place to consider technological developments and tests based on new technologies. Indeed, licences for disposal are granted by the authorities on the basis of demonstrated and confirmed technologies. However, progress made in the URL should be subject to additional authorisations once the performance of new technologies or processes has been demonstrated.

Given the complexity of the issues on the one hand, and the fact that these are relatively recent activities, international co-operation plays a major role. It translates into cross-participation in research activities in URLs and exchanges during workshops and conferences. Benchmarking and comparison activities also make it possible to collectively improve the understanding of systems, characterisation and modeling techniques and methodologies, as well as the evaluation of technologies proposed for the construction and operation of geological repositories.

References and further reading

General reading

Andersson, J. (1999), *A Study on the Co-operation of Research in Underground Facilities Within the EU on Aspects of Disposal of Radioactive Waste*, EC DOC.XII-53-99.

Baumgartner, P. and P.M. Thompson (2007), "Twenty Plus Years of Underground Research at Canada's URL", *International Symposium on Nuclear Energy (SIEN'07), Nuclear Power – A New Challenge*, Bucharest, Romania, 15-19 October 2007.

Blechschmidt, I. and S. Vomvoris (2010), "Underground Research Facilities and Rock Laboratories for the Development of Geological Disposal Concepts and Repository Systems", in *Geological Repository Systems for Safe Disposal of Spent Nuclear Fuels and Radioactive Waste*, J. Ahn, M.J. Apted (eds.), Woodhead Publishing Series in Energy, No. 9, Woodhead Publishing Limited, Oxford, pp. 82-118.

Faybishenko, B., J. Birkholzer, D. Sassani, P. Swift (2016), International Approaches for Deep Geological Formations: Geological Challenges in Radioactive Waste Isolation—Fifth Worldwide Review, Lawrence Berkeley National Laboratory, LBNL Report #: LBNL-1006984.

Development

Disposal of Nuclear Waste: Geological Challenges in Radioactive Waste Isolation, Fifth Worldwide Review LBNL-1006984, 2016.

Mazurek, M., et al. (2008), "Transferability of Geoscientific Information from Various Sources (Study Sites, Underground Rock Laboratories, Natural Analogues) to Support Safety Cases for Radioactive Waste Repositories in Argillaceous Formations", *Physics and Chemistry of the Earth*, 33, S95-S105.

McCombie, C. and W. Kickmaier (2000), "Underground Research Laboratories: Their Roles in Demonstrating Repository Concepts and Communicating with the Public", *EURADWASTE 1999, Radioactive Waste Management Strategies and Issue*s, *Fifth European Commission Conference on Radioactive Waste Management and Disposal and Decommissioning*, Luxembourg, 15-18 November 1999, European Commission Report EUR 19143, pp. 274-281.

NEA (2024), "NEA and METI International Workshop on Joint Utilisation of Underground Research Laboratories for R&D Projects: Horonobe, Japan, 1-3 November 2022", OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_97675.

NEA (2020), *International Roundtable on the Final Disposal of High-Level Radioactive Waste and Spent Fuel*, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_39718.

NEA (2013), *Underground Research Laboratories (URL)*, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_48874.

NEA (2008), *Moving Forward with Geological Disposal of High-activity Radioactive Waste*, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_14450.

NEA (2001), *The Role of Underground Laboratories in Nuclear Waste Disposal Programmes*, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_48874.

NEA (2000a), *Geological Disposal of Radioactive Waste: Review of Developments in the Last Decade*, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_13324.

NEA (2000b), *Progress Towards Geologic Disposal of Radioactive Waste: Where Do We Stand?*, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_13268.

NEA (1999), *Confidence in the Long-term Safety of Deep Geological Repositories – Its Development and Communication*, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_13274.

Palonen, E., S. Mustonen and T. Äikäs (2008), "Underground Repository Facility for Nuclear Waste – Underground Characterisation and Research Facility Onkalo", *ITA-AITS World Tunnel Congress 2008 – Underground Facilities for Better Environment and Safety*, Agra, India, 19-25 September 2008, pp. 39-47.

Savage, D. (ed.) (1995), *The Scientific and Regulatory Basis for the Geological Disposal of Radioactive Waste*, John Wiley and Sons, Chichester.

Wildi, W., et al. (2000), *Disposal Concepts for Radioactive Waste, Final Report*, Federal Office of Energy, Bern, Switzerland.

Technical reading

Baumgartner, P. and P.M. Thompson (2007), *Twenty Plus Years of Underground Research at Canada's URL*, International Symposium on Nuclear Energy (SIEN'07), Nuclear Power – A New Challenge, Bucharest, Romania, 15-19 October 2007.

Bossart, P. and M. Thury (eds.) (2008), *Mont Terri Rock Laboratory Project, Programme 1996 to 2007and Results*, Reports of the Swiss Geological Survey 3, Swisstopo, Wabern, Switzerland.

Chandler, N.A. (2003), *Twenty Years of Underground Research at Canada's URL,* WM'03 Conference, Tucson, Az, United States.

Dixon, D.A., J.M. Martino and D.P. Onagi (2009), *Enhanced Sealing Project (ESP): Design, Construction and Instrumentation Plan*, Nuclear Waste Management Organisation (NWMO) Technical Report APM-REP-01601-0001, Toronto, Canada.

Fairhurst, C., et al. (1993), *Stripa Project Overview Report, Vol. I: Executive Summary*, OECD/NEA International Stripa Project 1980-1992, Swedish Nuclear Fuel and Waste Management Co. (SKB), Stockholm, Sweden.

Gnirk, P. (1993), *Stripa Project Overview Report, Vol. II: Natural Barriers*, OECD/NEA International Stripa Project 1980-1992, Swedish Nuclear Fuel and Waste Management Co. (SKB), Stockholm, Sweden.

Gray, M. (1993), *Stripa Project Overview Report, Vol. III: Engineered Barriers*. OECD/NEA International Stripa Project 1980-1992, Swedish Nuclear Fuel and Waste Management Co. (SKB), Stockholm, Sweden.

Haijtink, B. and C. Davies (eds.) (1998), "*In Situ* Testing in Underground Research Laboratories for Radioactive Waste Disposal", *Proceedings of a CLUSTER Seminar*, Alden Biesen, Belgium, 10-11 December 1997, European Commission Report EUR 18323.

IAEA (forthcoming), *The Use of Results Obtained from Underground Research Laboratory Investigations*, IAEA-TECDOC, IAEA, Vienna, Austria.

Delay, J., P. Bossart, X.L. Li, I. Blechschmidt, M. Ohlsson, A. Vinsot, C. Nussbaum and N. Maes, (2014), "Three decades of underground research laboratories: what have we learned?", Geological Society, London, Special Publications 2014, v.400, pp. 7-32.

Delay, J., M-D. Salsac, E. Huret, S. Dewonck, J-M. Bosgiraud and G. Armand (2020) "ANDRA'S Underground Research Laboratory in Bure: Major Role in the Cigéo", WM2020 Conference, 8-12 March 2020, Phoenix, Arizona, United States.

Kickmaier, W. and I. McKinley (1997), "A Review of Research Carried Out in European Rock Laboratories", *Nuclear Engineering and Design*, 176, pp. 75-81.

NEA (2001), "Going Underground for Testing, Characterisation and Demonstration", NEA/RWM/(2001)6/REV, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_17646.

Olsson, O. (1998), "The Role of the Äspö Hard Rock Laboratory in the Swedish Nuclear Waste Programme", *Proceedings of Waste Management '98.*

Ota, K. (ed.) (1999), *Proceedings of an International Workshop for the Kamaishi In Situ Experiments*, Kamaishi, Japan, 24-25 August 1998, JNC TN7400 99-007, Japan Atomic Energy Agency (JAEA), Tokai, Japan.

Ota, K., H. Abe and T. Kunimaru (eds.) (2011), *Horonobe Underground Research Laboratory Project:Synthesis of Phase I Investigations 2001-2005*, Volume "Geoscientific Research", JAEA-Research 2010-068, Japan Atomic Energy Agency (JAEA), Tokai, Japan.

Priyanto, D., J. Hansen, R. Farhoud and K. Birch (2019), *Lessons Learned from the 10 Years of Enhanced Sealing Project (ESP) at the Former Canada's Underground Research Laboratory (2008 to 2018)*, 4th Canadian Conference on Nuclear Waste Management, Decommissioning and Environmental Restoration, Ottawa, ON, Canada, 8-11 September 2019.

Priyanto, D.G. (2023), "The Enhanced Sealing Project (ESP) at the Underground Research Laboratory in Canada: Sixteen Years and Counting?", Proceedings of the ASME 2023 International Conference on Environmental Remediation and Radioactive Waste Management*,* ASME 2023 International Conference on Environmental Remediation and Radioactive Waste Management, ICEM 2023, 6-8 October 2023, V001T10A010, ASME, Stuttgart, Germany.

Saegusa, H. and T. Matsuoka (eds.) (2011), *Final Report on the Surface-based Investigation (Phase I) at the Mizunami Underground Laboratory Project*, JAEA-Research 2010-067, Japan Atomic Energy Agency (JAEA), Tokai, Japan.

SKB (1996), *Äspö Hard Rock Laboratory, 10 Years of Research*, Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Thompson, P. and D. Priyanto (2016), *Canada's Underground Research Laboratory (1980-2014),* WM2016 Conference, 6-10 March 2016, Phoenix, AZ, United States.

US DOE (2001), *Proceedings of the Conference on Geologic Repositories: Facing Common Challenges*, Denver, Colorado, 31 October-3 November 1999, United States Department of Energy.

Appendix A: Websites for URLs and their management organisations

Andra

www.andra.fr/

Äspö Hard Rock Laboratory

www.skb.com/research-and-technology/laboratories/the-aspo-hard-rock-laboratory/

Asse Mine

www.bge.de/en/asse/

BGE

www.bge.de/en/

CIGÉO

https://meusehautemarne.andra.fr/landra-en-meusehaute-marne/installations/le-laboratoire-souterrain

Gorleben

www.bgr.bund.de/DE/Themen/Endlagerung/Standorte/Gorleben/gorleben_node.html

Grimsel Test Site

www.grimsel.com/

HADES underground laboratory

www.euridice.be/fr/content/le-laboratoire-souterrain-hades

science.sckcen.be/en/Facilities/HADES

Horonobe Underground Research Center

www.jaea.go.jp/english/04/horonobe/index.html

IRSN

www.irsn.fr/page/la-station-experimentale-de-tournemire

Konrad

www.bge.de/en/konrad/

Korea Underground Research Tunnel (KURT)

www.kaeri.re.kr/eng/board?menuId=MENU00724&siteId=null

Mizunami Underground Research Laboratory

www.jaea.go.jp/04/tono/miu_e/project/project.html

Mont Terri Project

www.mont-terri.ch/

Morsleben

www.bge.de/en/morsleben

Olkiluoto Research Tunnel - ONKALO

www.posiva.fi/en/index/finaldisposal/researchandfinaldisposalfacilitiesatonkalo.html

SKB

www.skb.com

Tono Geoscience Center

www.jaea.go.jp/04/tono/tgc_e/index_e.html

Whiteshell Underground Research Laboratory

www.aecl.ca/radioactive-waste/project-sites/whiteshell-laboratories/

Appendix B: Report of the NEA and METI International Workshop on Joint Utilisation of Underground Research Laboratories for R&D projects (Horonobe, Japan, 1-3 November 2022)

The report "NEA and METI International Workshop on Joint Utilisation of Underground Research Laboratories for R&D Projects: Horonobe, Japan, 1-3 November 2022" can be found on the NEA website at the following address:

www.oecd-nea.org/jcms/pl_97675/nea-and-meti-international-workshop-on-joint-utilisation-of-underground-research-laboratories-for-r-d-projects