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NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Foreword

The concept of engineered geologic disposal has been developed for the safe long-term management of long-lived radioactive waste. This involves emplacement of radioactive waste in deep geological repositories that contain and isolate the waste and, consequently, protect humans and the environment. A nuclear waste repository takes decades to develop and the best available technologies and engineering design are applied to achieve long-term safety. Throughout the development of a repository, the feasibility, safety and appropriateness of the proposed system must be proven to all stakeholders before a decision can be made and the development process can progress. There are several such decisions underpinned by safety reviews until the licensing of the final closure of a repository, and there is a commitment on all stakeholders to continuously improve the technical solutions in a virtuous process of optimisation.

Decision making requires practical demonstrations of key technical elements in order to demonstrate 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. In areas such as demonstrating operational safety, acquiring geological information at a repository scale and in constructional and operational feasibility, only URLs can provide reliable *in situ* data. URLs can also provide tangible benefits in enhancing participation by the general scientific community and confidence amongst both technical and non-technical stakeholders.

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 to build confidence in national programmes. The present brochure builds upon the 2001 document and integrates recent URL literature and the strategic outlook of NEA countries on URLs into an easily accessible document for an audience of both specialists and non-specialists in radioactive waste disposal.

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1. Introduction

The concept of engineered geologic disposal has been developed for the safe long-term management of long-lived radioactive waste. This involves emplacement of radioactive waste in deep underground repositories that provide the long-term safe containment and isolation of the waste, and subsequently, 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 to achieve its long-term safety. Throughout the development of a repository, the feasibility, safety and appropriateness of the proposed system must be proven to all stakeholders before a decision can be made and the development process can progress. There are several such decisions underpinned by safety reviews until the licensing of the final closure of a repository, and there is a commitment on the part of all to continuously improve the technical solutions in a virtuous process of optimisation.

Decision making requires practical demonstrations of key technical elements in order 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. In areas such as demonstrating operational safety, acquiring geological information at a repository scale and in constructional and operational feasibility, only URLs can provide reliable *in situ* data. URLs can also provide tangible benefits in enhancing participation by the general scientific community and confidence amongst both technical and non-technical stakeholders. Many nuclear waste management programmes have advanced their repository designs and are moving towards implementation of disposal (e.g. Sweden, Finland, France). These programmes have made extensive use of URL for research and development work including important developments in 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.

As the URL activities continue to evolve, this brochure complements the information provided in the literature[1] by integrating information directly from NEA member countries in a strategic framework.

This document provides an overview of:

- the purpose and types of URLs that have been developed and are in operation or planned in NEA member countries to date (Chapter 2);
- the roles of URLs in repository development (Chapter 3);

1. See the 2010 review paper by Blechschmidt and Vomvoris.

- the aspects to consider when planning a URL during stepwise repository development (Chapter 4);
- URLs experience in the past decade (Chapter 5);
- opportunities and benefits of international co-operation in relation to URLs (Chapter 6).

Lessons learnt specifically from two URLs are presented in this brochure to enhance future strategic URL activity planning (Boxes 5.1 and 5.2). Details of other 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 often associate 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 be 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 methods, disposal, sealing and closure techniques, etc.; *ii)* the performance of engineered materials.
- *Technology development*. The development of equipment, techniques, and expertise for site characterisation, testing, monitoring techniques 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 in which site characterisation and testing activities are carried out along with technology development and demonstration activities in support of the development of deep geological repositories for radioactive waste.

URLs are located in geological environments that are considered to be suitable for repository implementation such as granite, salt, clay/shale or volcanic tuff. They may be constructed at depths of a few hundred metres (up to a thousand metres) underground, as is usually proposed for waste disposal, or at shallower depths. 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.

Purpose of URL

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 the actual repository.

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 their interactions;
- demonstrate the robustness of the design and to show the potential areas of optimisation of engineering components and processes;
- train personnel for safe operation of a future repository;
- build confidence with stakeholders for their understanding of the important processes governing repository performance.

Types of URL

Among the various types of URL, two broad categories 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, but provide information that may support disposal elsewhere.

- *Site-specific URLs*. Facilities that are developed at a site that *is considered* as a potential site for waste disposal and may, indeed, be a precursor to or 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 very useful at early stages of repository programmes. For instance, generic field investigations were carried out at the Switzerland Grimsel Test Site prior to the selection of a particular host geologic formation, whereas specific investigations were launched later in the Mont Terri road tunnel so as to study a clay formation that is being considered as a potential host rock elsewhere in Switzerland.

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 already existing excavations such as mines and tunnels. Advantages of using an existing mine or underground access include: *i)* makes use of the initial excavation and existing mine maintenance and safety infrastructure; *ii)* easier to get planning permissions to extend work in an existing mine or tunnel as opposed to the development of a new site. URLs that are built on already existing infrastructures benefit from the cost-saving opportunities for gaining 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 only 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 pre-construction (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, in confidence building and communicating the underground research progress to the public, a purpose-built generic URL can be designed to accommodate convenient visitor access in order to maintain communications with the public regarding the developmental progress of the repository programme. The trade-off is that these purpose-built URLs require substantial resource commitment associated with the full cost of excavation, construction and operation of the underground services.

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

Often 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 for confirming 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. Similar to the generic URLs, general research and development may also be carried out at the site-specific URLs, if required, provided that these activities do not cause any detrimental effects to the disposal operations or affect any future safety of disposal at the site. A site-specific URL may stay open after its associated repository is closed, providing opportunities for long-term monitoring and verification of engineered barrier and repository performance (often called performance confirmation), or it may be closed when the necessary research is complete. 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 490-800 m. Mined cavern at 950 m. • Waste emplacement at 511 m and 750 m levels.	*Managing organisation* • GSF (now Helmholtz Zentrum München). *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. Since 2009, BfS has been operating the Asse Mine under nuclear law which has more pronounced requirements than Mining Law. The preferred management option of the emplaced radioactive waste is to retrieve the waste in order to ensure long-term safety.*]	
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* • 360-410 m.	*Managing organisation* • SKB. *Remarks* • Galleries in former iron mine. Operated 1976-1992.	Canada, Finland, France, Japan, Spain, Switzerland, United States.
Grimsel Test Site (GTS)	*Host rock* • Granite. *Location* • In the Grimsel region of Switzerland. *Depth* • 450 m.	*Managing organisation* • Nagra. *Remarks* • Gallery from a service tunnel of a hydroelectric project. Operating since 1984.	Czech Republic, France, Germany, Japan, Spain, Sweden, United Kingdom, Finland, South Korea, 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* • 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.

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
Climax	*Host rock* • Granite. *Location* • Colorado, United States. *Depth* • 420 m.	*Managing organisation* • DOE. *Remarks* • Drift mined from existing excavations. Spent fuel disposal experiments conducted in 1978-1983.	
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* • France.	*Managing organisation* • Andra. *Remarks* • Galleries in potash mine. Operated 1986-1992.	
Fanay-Augères	*Host rock* • Granite. *Location* • Limousin, France.	*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.

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* • 230 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, Spain, Netherlands, Switzerland.
AECL Underground Research Laboratory	*Host rock* • Granite. *Location* • Lac du Bonnet, Manitoba, Canada. *Depth* • 240-420 m.	*Managing organisation* • AECL. *Remarks* • Operated 1984-2006. URL officially closed on 17 Nov. 2010.	France, Japan, Sweden, Finland, United States.
Mizunami Underground Research Laboratory (MIU)	*Host rock* • Granite. *Location* • Gifu Prefecture, central Japan. *Depth* • Research galleries at 300 m (in operation), 500 m (under construction) and 1 000 m (planned).	*Managing organisation* • JAEA. *Remarks* • Under construction since 2002. Excavation of two shafts started in 2003 and construction of research galleries completed at 300 m level in 2008 and started at 500 m level in 2011. R&D during excavation ongoing since 2004 and R&D at research gallery at 300 m level ongoing since 2010.	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* • Hokkaidō Prefecture, northern Japan. *Depth* • Research galleries at 140 m and 250 m (in operation), 350 m (to be constructed) and 500 m (planned).	*Managing organisation* • JAEA. *Remarks* • Under construction since 2005. Excavation of two shafts started in 2005 and construction of research galleries at 140 m level in 2009 and at 250 m level in 2011. Excavation of third shaft started in 2011. R&D during excavation ongoing since 2005 and R&D at research galleries ongoing since 2010.	France, Switzerland.
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.	
Korea Underground Research Tunnel (KURT)	*Host rock* • Granite. *Location* • South Korea. *Depth* • 90 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* • 500 m.	*Managing organisation* • Posiva. *Remarks* • Received a building permit for the facility in August 2003 and excavation began in 2004. Posiva plans to submit an application for a license to construct the repository around 2012.	
Gorleben	*Host rock* • Salt dome. *Location* • Lower Saxony, Germany. *Depth* • About 900 m below ground.	*Managing organisation* • BfS. *Remarks* • Shafts constructed 1985-1990, moratorium between 2000 and 2010, resumption of underground site characterisation in 2010.	
Konrad	*Host rock* • Limestone covered with shale. *Location* • Germany; southeast Lower Saxony. *Depth* • 800-1 300 m below ground.	*Managing organisation* • BfS. *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. *Remarks* • Former salt and potash mine, repository for LLW and ILW since 1981 (disposal operations terminated in 1998). Licensing procedure for decommissioning initiated.	

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* • Operating since 1982, licensed transuranic (TRU) waste repository since 1999.	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* • *In situ* testing began in 1996; construction of an exploratory side tunnel completed in 1998. Operation stopped in 2009.	
Bure	*Host rock* • Shale (indurated clays), Callovo-Oxfordian Argillites. *Location* • Meuse/Haute Marne France. *Depth* • 450-500 m.	*Managing organisation* • ANDRA. *Remarks* • Potential repository site, in operation since October 2004. The URL is not allowed to receive any waste and will not be integrated in the repository. The application for the construction licence of the repository will be submitted in 2015.	Switzerland, Germany, Japan.

3. The Role of URLs in Repository Development

Following more than 40 years of work on specific scientific issues, the roles played by generic and site-specific URLs are distinctly different, although 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 emphasis is placed on developing an understanding of the processes that occur in rocks, or whether the emphasis is on the collection of site-specific data. Generic URLs perform a somewhat different role, in that they could accept studies to complement a site-specific URL programme. 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.	*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 assessment 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, address environmental impact assessment issues. *Testing of final repository design 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 OECD/NEA between 1980 and 1992, provided valuable geohydrological information on granitic rock at a depth of 350-400 m and also developed technologies for measuring thermodynamic, geophysical and geochemical properties of the Stripa granite. Later URLs have been developed for reasons such as to test and to 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 (Thury, 2008). Other rock types that have been extensively studied through other generic URLs include crystalline rock, argillaceous clay and rock salt.

Generic URLs are commonly located at sites with geological properties that are similar to those being considered for the proposed disposal option. Some generic URL sites are selected because they are potentially less favourable than actual disposal 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 their different rock characteristics from the proposed host formation which provide 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).

Generic URLs play a unique role which cannot be replaced by a site-specific URL in some cases. For example, experiments that are unfavourable to be performed in a site-specific URL (due to possible interference to repository construction/ operation) can be carried out in a generic URL.

The role of site-specific URLs

Work in site-specific URLs is sometimes being considered as the continuation of a site-characterisation programme. As a site-characterisation programme continues and eventually reaches a stage when specific site 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, optimisation of excavation techniques, etc.), a site-specific URL can be considered. In designing a site-specific URL programme, it is crucial to minimise the extent of 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 a very low permeability as obtaining reliable data using surface boreholes will be extremely difficult and specialised testing techniques will have to be used *in situ*.

4. The Planning of a URL During Stepwise Repository Development

Regardless of the type, all URLs play a prominent role in the development of a repository. URLs provide a platform to obtain the important scientific evidence for better understanding the technical aspects (such as geological, hydrogeologic, geochemical characteristics of a site) for repository development. 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.

Stepwise repository development and supporting work in URLs

Repository development proceeds in stages which include planning, technical development and scientific research, siting, construction, licensing, operation, and eventual closure of the disposal facility. Developing a geological repository in a stepwise manner allows experience and information gained in each stage to be reviewed so as to confirm the existence of sufficient information prior to proceeding to the next phase. At different stages of the repository development process, the following URL activities have been defined to achieve the required scientific/ technical information:

- *Concept development*:
  - research to understand general characteristics and processes in relevant geologic environments in order to develop generic models of rock and hydrogeologic response, transport of contaminants, and overall repository performance;
  - 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 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 excavation;
  - 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 the 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, etc. 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 on 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. This fact also further emphasises the effectiveness of generating the necessary scientific knowledge using a tripartite approach, i.e. generic URL, site-specific URL and surface-based investigations.

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. One must be certain that the URL site will not be considered for repository construction.	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 minimise uncertainties (as compared to surface-based investigations) and specific data relevant to detailed design and licensing safety assessment can be obtained. Specific URL allows demonstration of repository concept at full 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. Relatively short time scale of experiments compared with time over which long-term safety assessment is required. 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 must be minimised. The comparative sizes of URL and actual repository may limit the scales of testing; scales of testing are also limited both temporally and spatially when compared with those required for long-term safety assessment (e.g. volume of rock tested possibly not representative). Practically impossible to determine the rock properties in detail over the full extent of the repository.

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 have the benefit of 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 also assisting in building confidence in underground disposal.

If, on the other hand, disposal of waste is a pressing concern, then 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 the 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; *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 less; supplementary data are 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 setting.

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

Development of a repository requires research and testing that may be very 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 one may argue 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.

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.

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 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.

Timing of site-specific URL development

A number of technical and administrative matters should be considered when deciding when to develop a site-specific URL.

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 the lack of this 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 only can 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 areas in which URLs are valuable is in the information that can be obtained 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 are 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. In order 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, 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 construction 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. Construction costs for a URL may easily be of the order of 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 Bure URL (France) as of 2010:

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

5. URL Experience in the Past Decade

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. Amongst 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 90s, the number of site-specific facilities has increased and a few new, purpose-built URLs have come to operation. These include:

- The Bure URL, located in Meuse/Haute-Marne; France (Figure 5.1), a site-specific URL purposely built to study a 155-million-year-old clay rock. The facility began its experimentations in October 2004 and since then has completed the first phase of tests at the Callovo-Oxfordian formation and is developing the next phase of underground testing.
- 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 to study the granite bedrock and groundwater conditions of the nearby Olkiluoto underground storage facility in 2003.

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

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. Development of equipment and testing methodologies, as well as basic engineering feasibility studies and collection of fundamental geologic data, were the priorities. Today, those types of activities are receiving decreasing emphasis

Figure 5.1: BURE URL installations

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

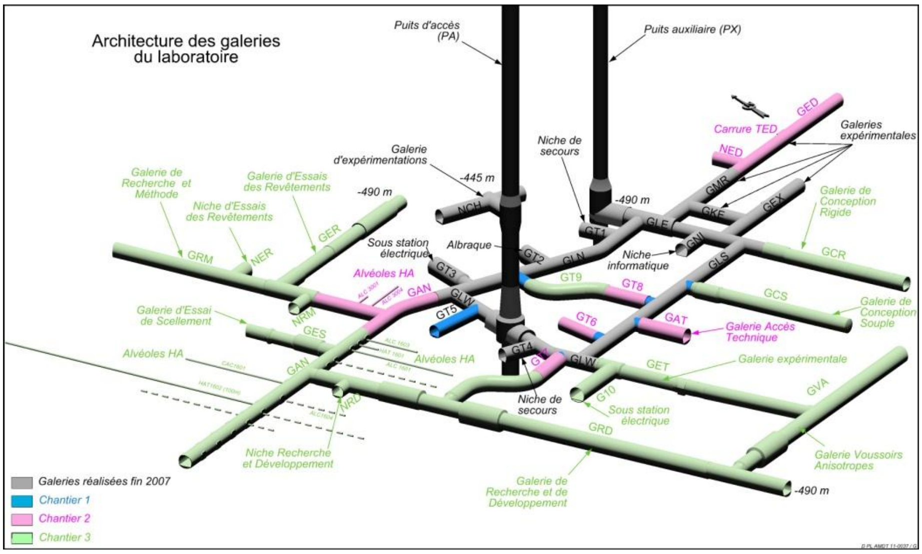


Figure 5.2: KURT URL

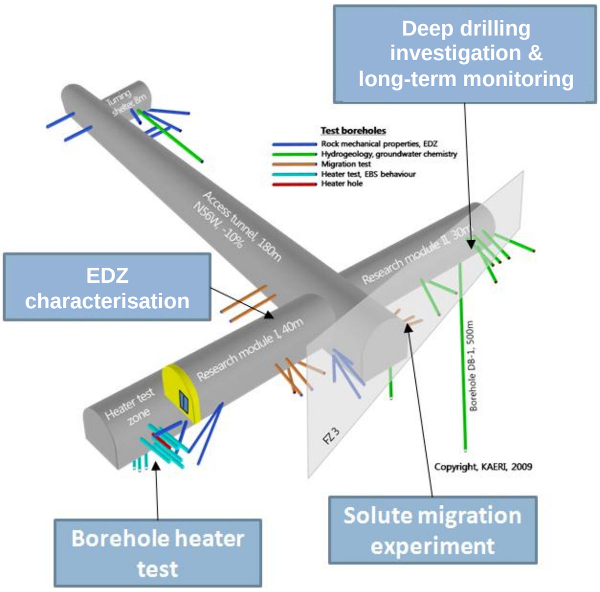
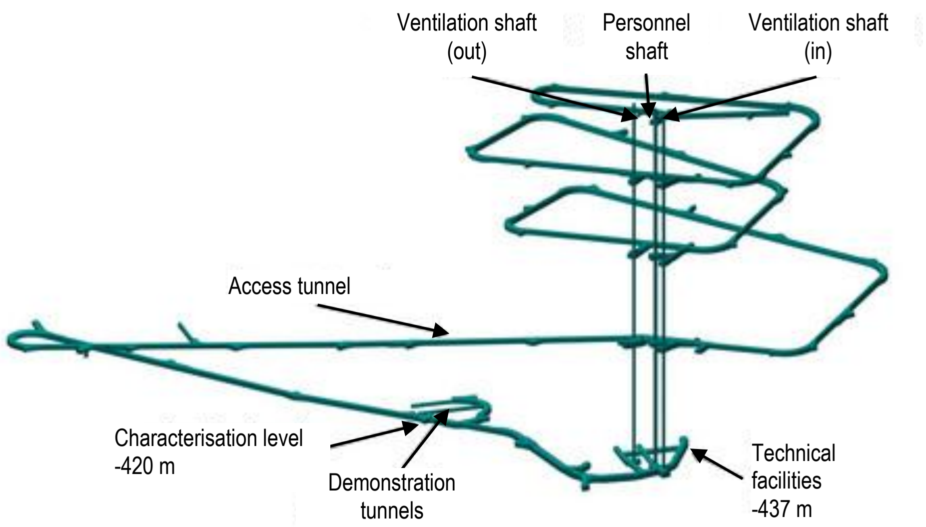


Figure 5.3: ONKALO



because of the information now available. Today, efforts are directed towards more integrated (and more complex) projects with two main characteristics:

- Field experiments under repository-relevant boundary conditions, i.e. 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. Increased emphasis is also being placed 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

See Appendix B for a list of acronyms

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. Development of equipment and procedures for brine permeability tests in halite at WIPP. Brine migration test at Asse. Specific equipments 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 ground penetrating radar tools which increase the depth of penetration in rock salt up to several hundred meters; 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.
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.
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. Application of geophysical methods at Grimsel Test Site, Tournemire and Stripa.

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

Objectives	Examples
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 and Bure. 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. 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. Demonstration of deep borehole drilling technique at Asse. 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 for vitrified waste at Bure. Packer tests for excavation-damaged zone measurements at Morsleben 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. Thermal-structural interactions tests at WIPP. Thermal-mechanical-hydraulic tests at AECL URL and Bure.

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

Objectives	Examples
(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. 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.
(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. 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. 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). 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).

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 different from that 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. URLs provide the opportunity to develop and test the tools that will be needed for characterisation of a repository and, just as important, 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 license 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.

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 develop first, 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 reflecting representing 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 up-scaling 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, 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 exposed 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 the geological environment under representative *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 as for example:

- 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 URL. 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.

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.
- The interaction between a heat-generating source (container simulation), the engineered barriers surrounding it and the surrounding geosphere were studied. These demonstrated strong T-H-M-C and biological linkages and the importance of understanding how the components interact.
- Information related to the evolution and performance of sealing system components developed from laboratory tests and simulations need to be tested at full scale in an environment relevant to a repository (e.g. container-buffer installations, full-scale tunnel plugs) and then their T-H-M evolution can be evaluated.

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.

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.

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, to be located at the selected site, Olkiluoto, technology researches 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 is expected to be complete by 2014. Site investigations have been carried out since the start of construction in conjunction with excavation.

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

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

6. International Co-operation

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 exchange of ideas, creativity and better quality research as well as peer review. The collective demand from several organisations reinforces 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 the 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 obtains the results of effort contributed by 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 research 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 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, suitability of potential geologic environment and technical feasibility can only be gained through underground verification and demonstration. All of these factors are of importance in building the safety case for a repository and the many existing and successfully operating URLs are providing 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 are 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, a cost-effective way to perform experiments as expenses are shared among nations, 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 also grows in importance. 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 and even after repository closure.

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., 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., 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.

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., 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 (Nuclear Energy Agency) (1999), *Confidence in the Long-term Safety of Deep Geological Repositories – Its Development and Communication*, OECD/NEA, Paris.

NEA (2000a), *Geological Disposal of Radioactive Waste: Review of Developments in the Last Decade*, OECD/NEA, Paris.

NEA (2000b), *Progress Towards Geologic Disposal of Radioactive Waste: Where Do We Stand?*, OECD/NEA, Paris.

NEA (2008), *Moving Forward with Geological Disposal of High-activity Radioactive Waste*, OECD/NEA, Paris.

Palonen, E., S. Mustonen, 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

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

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, Paul (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, Malcolm (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., 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 (International Atomic Energy Agency) (forthcoming), *The Use of Results Obtained from Underground Research Laboratory Investigations*, IAEA-TECDOC, IAEA, Vienna, Austria.

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

NEA (2001), *Going Underground for Testing, Characterisation and Demonstration*, NEA/RWM/(2001)6/REV, OECD/NEA, Paris.

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, 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.

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

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

Appendix A: Websites for URLs and Their Management Organisations

URL websites

Äspö Hard Rock Laboratory

www.skb.se/Templates/Standard____25506.aspx

Asse Mine

www.endlager-asse.de/cln_135/EN/1_Home/home_node.html

BfS

www.bfs.de/en/bfs

Gorleben

www.bfs.de/en/endlager/erkundungsbergwerk_gorleben

Grimsel Test Site

www.grimsel.com/

HADES underground laboratory

www.sckcen.be/en/Our-Research/Research-facilities/HADES-Underground-laboratory

Horonobe Underground Research Center

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

IRSN

www.irsn.fr/EN/Pages/home.aspx

Konrad

www.endlager-konrad.de/cln_117/DE/Home/home_node.html_nnn=true

Korea Underground Research Tunnel (KURT)

ehome.kaeri.re.kr/snsd/eng/institution/institution3.htm

Mizunami Underground Research Laboratory

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

Mont Terri Project

www.mont-terri.ch/

Morsleben

www.bfs.de/en/endlager/endlager_morsleben

Olkiluoto Research Tunnel

www.posiva.fi/en/research_development/onkalo

ONKALO

www.posiva.fi/en/research_development/onkalo

SKB

www.skb.se/default____24417.aspx

Tono Geoscience Center

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

Whiteshell Underground Research Laboratory

www.brandonsun.com/breaking-news/whiteshell-labs-closes-underground-facility-forever-111511344.html?viewAllComments=y

URL management organisation websites

AECL	www.aecl.ca/site3.aspx
ANDRA	www.andra.fr/international/index.html
BfS	www.bfs.de/en/bfs
EIG EURIDICE	www.euridice.be/eng/010301infrastructuur.shtm
GSF	www.helmholtz-muenchen.de/en/start/index.html
IRSN	www.irsn.fr/EN/Pages/home.aspx
JAEA	www.jaea.go.jp/english/index.shtml
KAERI	www.kaeri.re.kr:8080/english/
SKB	www.skb.se/default____24417.aspx
Nagra	www.nagra.ch/
Posiva	www.posiva.fi/en/
PURAM	www.rhk.hu/en/
Swisstopo	www.swisstopo.admin.ch/internet/swisstopo/en/home.html
US DOE	www.ne.doe.gov/

Appendix B: List of Acronyms

AECL	Atomic Energy of Canada Limited, Canada
ANDRA	National Agency for Radioactive Waste Management, France
BfS	Federal Office for Radiation Protection, Germany
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
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 of the OECD, Paris, France
OECD	Organisation for Economic Co-operation and Development, Paris, France
Posiva	Radioactive waste management company in Finland
PURAM	Public Agency for Radioactive Waste Management, Hungary
QA	Quality assurance
R&D	Research and development
SEDE	NEA Co-ordinating Group on Site Evaluation and Design of Experiments for Radioactive Waste Disposal
SNHGS	Swiss National Hydrological and Geological Survey
SKB	Nuclear Fuel and Waste Management Company, Sweden
TRU	Transuranic waste
URF	Underground Research Facility, Mol, Belgium

URL	Underground Rock (or Research) Laboratory, generic term as well as specific facility in Lac du Bonnet, Canada
US DOE	United States Department of Energy
WIPP	Waste Isolation Pilot Plant, Carlsbad, New Mexico, United States