Canada's Underground Research Laboratory (1980-2014) – 16274

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ABSTRACT

In 1980, Canada initiated a long-term, comprehensive research and development program of geologic characterization and large-scale in situ geotechnical experiments in a subsurface facility, the Underground Research Laboratory (URL). The URL was excavated specifically to evaluate the concept of permanent disposal of used CANDU® nuclear reactor fuel in a deep geological repository (DGR) constructed in Canadian Shield granite. Key phases of the URL included siting, detailed site characterization and monitoring, construction, operation, decommissioning, and closure. Much collaborative research with international organizations was undertaken at the URL and continues, even after the closure of the facility, through the ongoing Enhanced Sealing Project (ESP). The ESP monitors the engineered performance of a full-scale composite shaft seal that was emplaced during URL closure to permanently seal the main URL access shaft across a sub-horizontal hydraulically active fracture zone. Currently the ESP is jointly funded by Canadian Nuclear Laboratories (CNL) (Canada), Posiva (Finland), and Andra (France), and monitoring is planned to continue until the end of 2016. Decades of programmatic experience at the URL have shown that knowledge continuity is integral to supporting the development of a safe geological disposal facility for high level nuclear waste. This paper outlines the history of the URL and describes some technical lessons learned from its 30-plus years of construction, operation, and closure activities.

INTRODUCTION

Geological disposal is one of the important components of the integrated approach to the back-end of the nuclear fuel cycle [1], and by the late 1970s deep geological disposal had become recognized internationally as a preferred option for the ultimate safe end point for high-activity, long-lived radioactive wastes [2]. Canada's Underground Research Laboratory (URL), located on the Canadian Shield in eastern Manitoba, was the first underground laboratory in the world to be constructed specifically to evaluate the concept of nuclear fuel waste disposal in a previously undisturbed geologic environment that was carefully characterized prior to excavation and during operation.

The URL was a generic facility (representative of geological conditions within the Canadian Shield in general and not site specific) [3]; it was built solely for research purposes and was never intended for eventual use as a site for disposal of any radioactive wastes. Starting in 1980, a comprehensive Research, Development and Demonstration (RD&D) program of geologic characterization and large-scale geotechnical experiments in granite was undertaken at the URL to evaluate the concept of permanent disposal of used CANDU® fuel in a Deep Geological Repository (DGR) constructed in Canadian Shield granite. Since the RD&D projects at the URL

were generic rather than site-specific, much collaborative research was undertaken at the URL over the course of its existence with international organizations from Finland, France, Japan, Korea, Sweden and the USA.

Before the underground workings were permanently closed in 2010, the URL was a member of the International Atomic Energy Agency (IAEA) Network of Centers of Excellence for underground laboratories. Even after the closure and sealing of the underground excavations and after the demolition of the URL surface facilities in 2014, collaboration with international organizations at the URL is continuing by means of the Enhanced Sealing Project (ESP) that started in 2009. The ESP involves the monitoring of instrumentation in and around a full-scale composite (concrete/clay) shaft seal acting to permanently seal the URL access shaft. The full-scale composite shaft seal is comparable to that likely to be installed at an actual DGR on closure. Currently the ESP is jointly funded by CNL (Canada), Posiva (Finland), and Andra (France), and monitoring of the experiment is planned to continue until the end of 2016.

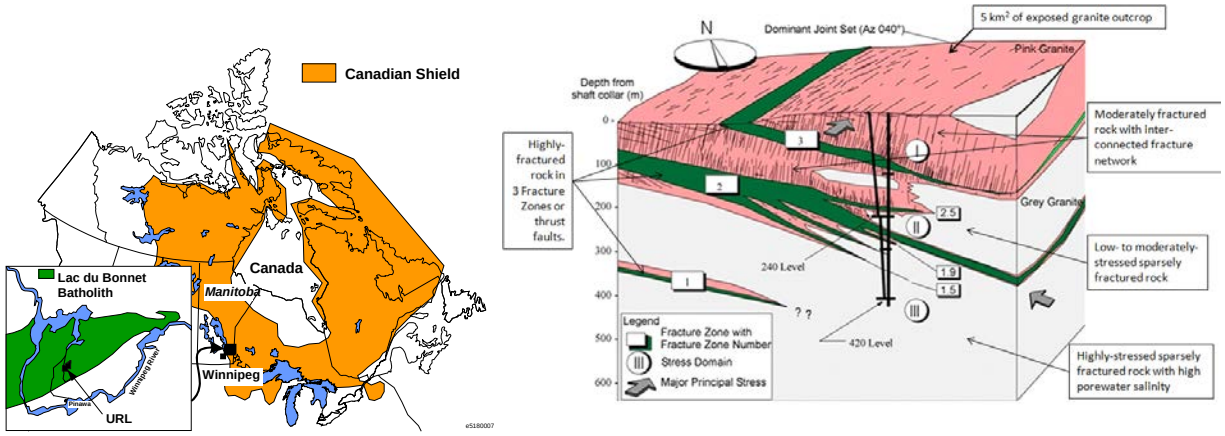
Several previous documents have summarized lessons learned from the URL prior to 2002 ([4], [5]). This paper presents more recent lessons learned from 2002 to 2015, focusing on several major experiments at the URL that have provided valuable data to support the eventual development of a safe DGR for highly radioactive wastes. This paper also notes how technical knowledge in the area of geologic waste disposal can be lost or diminished through major organizational and personnel changes.

CANADA'S UNDERGROUND RESEARCH LABORATORY (URL)

Site Location, Geological Setting, and Excavation

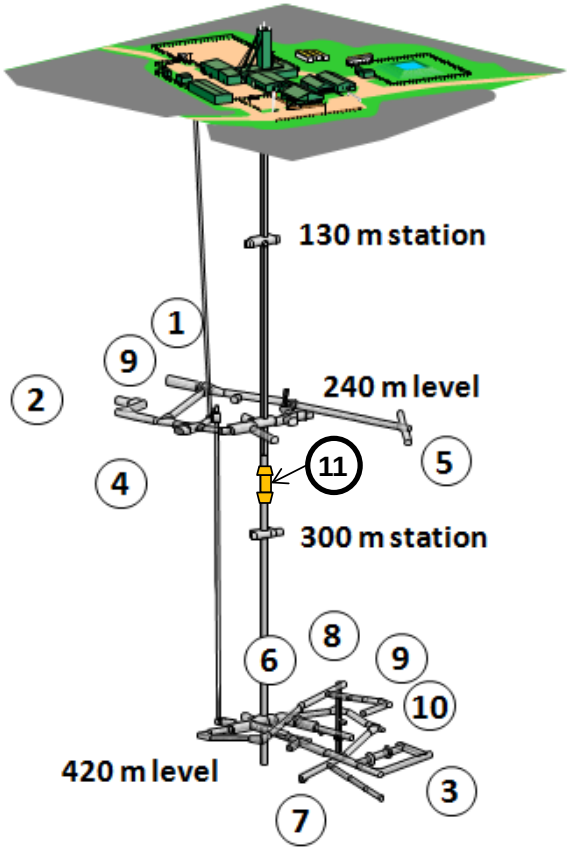
The URL site is located in Precambrian crystalline rocks on the western edge of the Canadian Shield in the Lac du Bonnet granite batholith (Figure 1a) [6]. The URL provided a representative geological environment in which to conduct in situ multidisciplinary experiments. The site had interesting and varied geology and was crosscut by two low-dipping thrust faults, or fracture zones, with a near-by deeper third thrust fault that terminated before passing below the URL excavations (Figure 1b). The blocks of rock between the thrust faults define different structural domains that can be distinguished by the presence of intrusions and segregations and by the pattern and frequency of sub-vertical fracturing, as well as by differing in situ stress regimes. The URL had a vertical main shaft and a ventilation shaft for accessing two working levels, at the 240 m level and the 420 m level, and two drilling stations, at depths of 130 m and 300 m (Figure 2). The main shaft was 443 m deep. Total excavated volume of the URL was 34,270 m^3 including approximately 1.6 km of horizontal excavations.

The RD&D conducted at the URL was intended to improve our fundamental understanding of engineering techniques and performance assessment issues, and to examine how several key aspects would support the development of an actual DGR. The studies were conducted both underground and on surface. The locations of the



(a) (b)

Fig. 1. Location and Geological Setting of the Underground Research Laboratory (URL)



Features of URL

- •34,270 m³ total excavated volume
- •1.6 km of horizontal excavations
- •2 working levels and 2 drilling stations
- •The depth of shaft is 443 m

1. Buffer/ Container Experiment (BCX)
2. Quarried Block Radionuclide Migration
3. Tunnel Sealing Experiment (TSX)
4. Solute Transport in Highly Fractured Rock
5. Solute Transport in Moderately Fractured Rock
6. Mine-by
7. Excavation Stability Study
8. Solute Transport in Excavation Damage Zone
9. Connected Permeability Tests
10. Heated Failure Tests
11. Enhanced Sealing Project (ESP)*

* Still on-going

Fig. 2. URL Excavations with Locations of the Major Operating Phase Experiments

major operating phase experiments are shown in Figure 2. Results from research at the URL have been used in the assessment of the feasibility and safety of geological disposal facilities for spent nuclear fuel in Canada [7], [8] and elsewhere through international collaborations.

PHASES OF THE URL

The URL was developed and subsequently operated by Atomic Energy of Canada Limited (AECL) from its inception in 1978 to November 2014, when demolition of the URL surface facilities was completed. At that time, as part of an organizational restructuring process, the facility became the responsibility of Canadian Nuclear Laboratories (CNL). From 1978 to 2014, there were five main phases of work at the URL, several of which overlapped.

Siting Phase (1978)

The URL siting phase began in 1978 when a regional reconnaissance was performed to identify a suitable location for the URL on the Lac du Bonnet batholith. A small set of screening criteria was established for selecting the site. The site had to be larger than 1 km^2, and it had to be predominantly outcrop and undisturbed by previous excavations. The site had to be within, but not close to, well-defined hydrologic boundaries. The site needed to be accessible, available for lease, near a source of power, and logistically convenient to AECL's Whiteshell Laboratories research facility near Pinawa, Manitoba [9].

Site Characterization and Monitoring Phase (1980-2014)

After the site was obtained, the site characterization phase had two objectives:

1. to characterize the geology, rock properties, fracture systems and hydrogeology that would provide the baseline boundary conditions for in situ experiments in the URL, and
2. to develop an approach to site characterization that would provide the necessary information for designing and constructing a repository in granite.

The site evaluation phase was largely surface-based. It involved surface mapping, airborne and ground geophysical surveys, surface water and meteorological data collection, and drilling of shallow boreholes for piezometric measurements. Installation of the monitoring system was carried out between 1980 and 1984 and site monitoring was conducted between 1981 and 2014. The experience gained at the URL was applied to develop an approach to underground characterization for a DGR [10].

Construction Phase (1983-1990)

The primary objective of the construction phase was to create a safe and efficient underground research facility [5]. The construction of surface buildings took place between 1982 and 1987. The excavation of shafts and tunnels for underground access took place between 1983 and 1990. The underground construction phase included a focus on rock mechanics, geological characterization, and the development of excavation and instrumentation techniques.

Operating Phase (1989-2004)

The initial program of URL operating phase experiments was developed in 1989, six years after the beginning of URL shaft excavation, and the operating phase experimental program was initiated in 1990. Most of the major URL experimental studies were carried out during the operating phase, as described in more detail in the following section.

Decommissioning Phase (2003-2015)

In response to a decision by Ontario Power Generation (OPG) to cease funding the operation of the URL after 2003 June, AECL chose to permanently close the URL. Funding for decommissioning and closure activities was provided by Canada's Nuclear Legacy Liabilities Program (NLLP). A decommissioning plan for the URL was prepared and approved, and decommissioning activities commenced in 2004. Closure of the underground facilities was completed in 2010 November. Demolition of surface facilities, followed by site refurbishment, took place in 2014 and 2015. Decommissioning of the URL is now essentially complete. At present the only RD&D study still ongoing is data collection from the ESP, which is scheduled to continue until the end of 2016.

STUDIES AT THE URL

The initial URL operating phase experiment plan was developed in 1989 and underwent peer review by a panel of leading Canadian scientists [11]. Major studies that have been conducted at the URL are listed under four broad experimental categories in Table 1. Locations of some of the major URL experiments are indicated in Figure 2. The important conclusions from the completed portions of the experimental programs were numerous and have been detailed in a number of reports that summarize experiment design, construction, operation, observations and conclusions ([10], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38],[39]).

Applications of the experiments at the URL were not limited to the development of geological disposal facilities in Canada, but also elsewhere. Many URL experiments were conducted as internationally funded projects that were long-term in nature and not easy to replicate elsewhere. Even after the experiments have long been completed, data and practical experience gained from the experiments continue to provide valuable resources to support the development of DGRs. Two potential uses of the data and information are described as follows. First, they can be used to support innovation in numerical modeling, such as finite element or finite difference models to simulate Thermal-Hydraulic-Mechanical (THM) processes (e.g., [13], [21]). These data sets can be used as verification tools to improve numerical modeling capabilities. Second, lessons learned from the URL experiments are useful for future design applications. Almost all of the experiments in TABLE I are applicable for these purposes. The two most recent experimental projects at the URL are described in the following sections.

TABLE I. Studies at the URL

SOLUTE TRANSPORT	• Solute transport in Highly Fractured Rock (HFR) • Solute transport in Moderately Fractured Rock (MFR)[(a)] • Quarried Block Radionuclide Migration Experiment (QBRME) [(a)] • In Situ Diffusion Experiment [(a)] • Excavation Damage Zone (EDZ) Solute Transport Test • Recharge Infiltration Experiment (RIEX) [(a)] • **URL Hydrogeological Monitoring [(a)(c)]** • JAERI Rockmass Experiment
EXCAVATED DAMAGE/EXCAVATION STABILITY	• In situ stress measurement program and stress characterization in deep boreholes and fractured rock[(a)] • Room 209 Excavation Response Test • ANDRA Engineering Blast Feasibility Study • Mine-by Excavation Response Test • Room 209 Connected Permeability Test • Heated Failure Tests (HFT) • Blast Damage Assessment Study (BDA) [(a)] • Mine-by Connected Permeability Test • Excavation Stability Study (ESS) • Thermal-Hydraulic Experiment (THE) • Thermal-Mechanical Stability Study (TMSS)
MULTI-DISCIPLINARY	• URL Characterization Program • Tunnel Sealing Experiment (TSX) [(a)] • Composite Seal Experiment (CSE) [(a)] • Engineering Design of Repository Sealing System (ENDRES) [(a)]
MATERIALS AND SEALING STUDIES	• Buffer/Container Experiment (BCE) • Isothermal Buffer-Rock-Concrete Plug Interaction Test (ITT) • Fracture Zone Grouting Experiment • High Pressure Grouting Simulator • Large Concrete Blocks • Light Backfill Placement Trials[(a)] • Seal and interface evaluation/ effect of salinity (SEAS) [(a)] • Buffer-coupon long-term test (BCLT) [(a)] • Dedicated microbial borehole and microbial studies[(a)] • Concrete-rock interface study (CRIS) [(a)] • **Enhanced Sealing Project (ESP)[(b)]**

Bolded words represent recent and/or ongoing studies

[(a)] These experiments were ongoing in 2002 [4].

[(b)] This experiment is currently ongoing and planned to continue until the end of 2016 [21].

[(c)] This work has been discontinued in 2014.

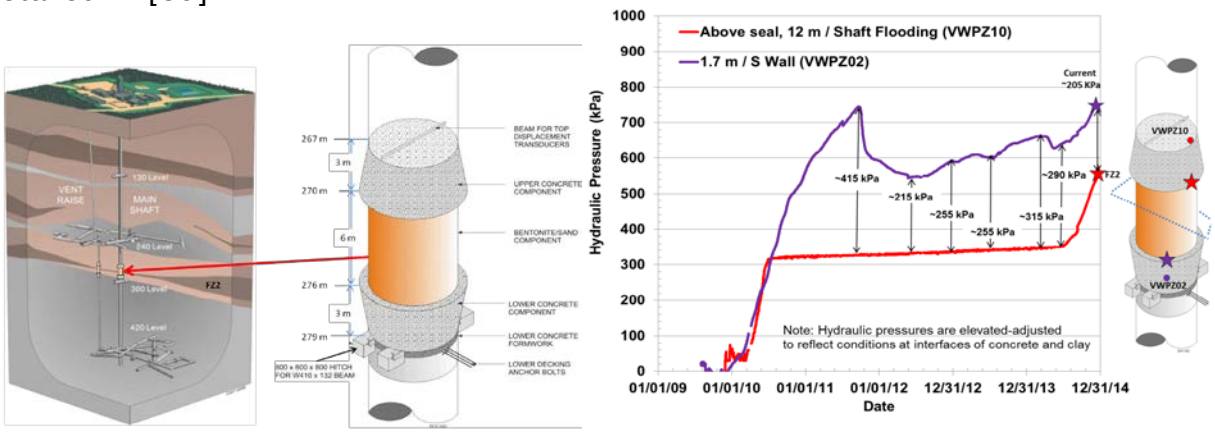
Enhanced Sealing Project (ESP) (2009-present)

As part of the decommissioning of the URL, a full-scale shaft seal was designed and installed in 2009 in the 5-m-diameter main shaft, which had been excavated by drill and blast techniques. The ESP provides a unique opportunity to observe how a full-scale shaft seal that is likely to be installed during closure of an actual DGR would perform during the period of groundwater recovery after the repository is closed. The seal was positioned where the main shaft intersects an ancient water-bearing, low-angle thrust fault (approximately 273 m deep) in granitic rock. The seal is intended to separate and limit the mixing of deep saline groundwater with water from the fresher, near-surface groundwater regime. The seal is a 6-m-thick, highly compacted (in situ) 40:60 blend of bentonite and quartz/feldspar sand that was sandwiched between and rigidly confined by a pair of 3-m-thick, keyed concrete components (Figure 3a). The target dry density of the bentonite/ sand component was 1.8 Mg/m^3. The bentonite-based component spans the fracture zone in the adjacent rock and extends approximately 1 m beyond the maximum identified vertical extent of the fracture.

The construction of a shaft seal, a necessary part of the closure activities, provided a unique scientific opportunity to also monitor, in real time, the evolution of a full-scale seal in the main shaft as the passive recovery of the regional groundwater regime occurred and the shaft above the seal flooded. The ESP was a jointly funded monitoring project developed to install over 100 sensors within and around the seal to monitor the THM responses of the shaft seal. The excavations below the seal were artificially flooded prior to seal construction using groundwater from a more permeable region of the fracture zone. This was done to accelerate the saturation of the seal and the groundwater recovery process. The first phase of the ESP was initially developed by AECL (Canada) and was financially supported between 2009 and 2013 by NWMO (Canada), SKB (Sweden), Posiva Oy (Finland) and Andra (France). As the URL decommissioning process continued, demolition of the URL surface facilities was completed in 2014. The URL surface facilities before and after decommissioning are shown in Figures 4a and 4b. Due to the very slow ongoing evolution/saturation of the seal and its surroundings, the second phase of ESP monitoring has now evolved to a stand-alone, lower frequency manual data collection program using portable read-out boxes. Since 2014, ongoing monitoring has been supported by Andra, Posiva, and CNL. Monthly monitoring is still continuing and planned until the end of 2016. The results of the ESP can be used to demonstrate the function of sealing of a DGR. As of end of 2014, the differential hydraulic pressure above and below the seal has been greater than that of hydrostatic pressure (Figure 3b).

Construction and data monitoring reports have been documented periodically ([14], [15], [16], [17], [18], [19], [20]). Data collected from the ESP can be used to support innovation in numerical modeling, particularly Hydraulic-Mechanical (HM) models and related safety assessment modeling (e.g., [19], [21]). The information gained from the ESP also provides confidence that a permanent composite seal could be successfully applied at an actual DGR. Recent results from the ESP (2009-15) are

detailed in [39].



(a) (b)

Fig. 3. Enhanced Sealing Project (ESP). (a) Geometry and Locations of the Bentonite-Concrete Seal at Canada's URL. (b) Hydraulic pressure evolution above and below the bentonite seal.

(a) (b)

Fig. 4. (a) Original URL facility layout. (b) ESP monitoring enclosure in October 2015

URL Hydrogeology Monitoring Program

Hydrogeological monitoring of the URL's rock mass was performed from 1984 to 1998 and from 2008 to the end of 2013. Between 2008 and 2014, the groundwater level in the rock mass surrounding the URL also was monitored in 22 boreholes located within approximately 500 m of the URL shaft. The URL hydrogeology monitoring program recorded and stored the hydrogeologic, hydrologic, and hydrogeochemical data collected at surface and from underground. The collected data have been used to maintain the hydrogeologic database to observe long-term trends within the Lac du

Bonnet batholith and to define background hydrogeologic, hydrologic, and hydrogeochemical conditions for URL experiments. The results of the URL hydrogeology monitoring and the ESP complement each other in the interpretation of groundwater hydraulic head contours at the URL.

After installation of the shaft seals in 2009 during decommissioning at the URL, the data from the hydrogeology monitoring program were combined with the ESP monitoring to identify groundwater level contours (Figure 5). During the decommissioning stage, the hydrogeological monitoring of the URL rock mass was included as part of environmental monitoring for the URL decommissioning. All the boreholes were decommissioned and data collection ended in 2014. A potential future use of these data could be to integrate the results of the URL hydrogeological monitoring program with the ESP results and the comprehensive site investigation and material characterization programs at the URL to support the development of advanced THM numerical modeling.

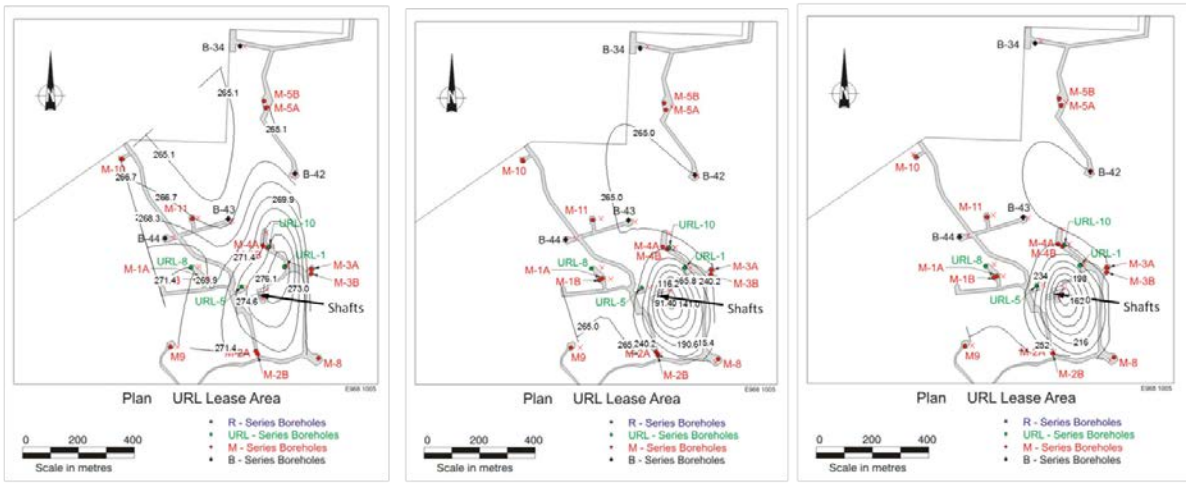


Fig. 5. Hydraulic Heads (MAMSL) at Fracture Zone 2, URL Site

INTERNATIONAL COLLABORATIONS

Many collaborative RD&D projects with both domestic and international organizations have been undertaken at the URL over its lifetime [5]. Without support from international collaborations, some of the experiments at the URL would not have been feasible. Before the URL underground workings were permanently closed in 2010, the URL was a member of the International Atomic Energy Agency (IAEA) Network of Centers of Excellence for underground laboratories. After the decision was made to decommission the URL, collaborations continued with the waste management organizations NWMO (Canada), SKB (Sweden), Posiva (Finland), and Andra (France) for the installation and monitoring of the ESP. Collaboration on the ESP with

international organizations is expected to continue until the end of 2016.

ORGANIZATIONAL CHANGES

Between 1978 and 1996, as mandated by the Canadian government, AECL took a lead role in developing waste disposal technology for Canada, with financial support from the government of Canada, Ontario Hydro and other members of the CANDU Owners Group (COG). The RD&D program at the URL was instrumental at the federal level in developing AECL's Environmental Impact Statement (EIS) for the Concept for Disposal of Canada's Nuclear Fuel Waste [7] in the mid-1990s. The Federal Environmental Assessment Review Panel that conducted a public review of the disposal concept acknowledged in their 1998 review report [40] that, from a technical perspective, the safety of Canada's concept for nuclear fuel waste disposal was adequately demonstrated. As part of the programmatic changes that also resulted from the panel's review, OPG (the principal producer of nuclear fuel waste in Canada), began funding used fuel disposal research in Canada between 1997 and 2002 under its Deep Geologic Repository Technology Program. Canada's Nuclear Fuel Waste Act of 2002 and the subsequent formation of the Nuclear Waste Management Organization (NWMO) also resulted from recommendations in the Federal Environmental Assessment Review Panel report.

Since 2002, the NWMO has been responsible for the planning the long-term management of Canada's used nuclear fuel. With the transition in Canada's deep geological disposal research to NWMO, in 2003 AECL made the decision to permanently close the URL. Due to the closing of the URL sooner than anticipated, some long-term experiments, such as the Buffer-Coupon Long-term Tests (BCLT), had to be abandoned. The Tunnel Sealing Experiment, another large-scale, internationally supported experiment, was decommissioned prematurely in 2005. The priorities between research and construction activities at the URL changed after the decision to decommission in 2003. Prior to the decommissioning phase (1978-2003), research activities generally had priority over construction activities, although the objectives of both were not always divergent [5]. The guiding principles were to maximize the benefits to the research program in order to best achieve the objectives set for the URL [5]. During the decommissioning phase, however, decommissioning activities had priority over research activities. Research activities required the approval and cooperation of the URL decommissioning program.

Organizational continuity is important to the successful development of a safe DGR. Over its lifespan, the URL experienced several major organizational and personnel changes. Many of the technical lessons learned from the URL have been lost or forgotten in the transition of used fuel disposal management responsibilities between different organizations. Over the years many technical specialists left the organization to pursue other opportunities or to retire. The successful transfer of knowledge from one generation or organization to the next will be important in the development of a safe DGR. Many studies at the URL, especially those related to sealing of the DGR (e.g., the ESP) will only be applied when an actual DGR is closed many generations from now.

CONCLUSIONS

For more than 35 years, Canada's URL carried out comprehensive in situ RD&D projects to support the design, feasibility and safety assessment of deep geological disposal of high level radioactive wastes. Much important information was produced through the URL experimental studies that are applicable to both Canadian and international nuclear waste management programs. International collaborations have been beneficial for the URL RD&D program and for the collaborators. Even after the complete demolition of the URL surface facilities, collaboration on the ESP between CNL, Posiva, and Andra is planned to continue until the end of 2016.

The span of more than 35 years that has covered URL siting, design, construction, operation, and decommissioning has produced invaluable practical experience as well as scientific and engineering data. Nevertheless, decisions made at political and programmatic levels have led to a series of transitions of used fuel disposal management responsibilities between different organizations in Canada, and many of the technical lessons learned from the URL have been lost or greatly diminished as a result. As a unique underground facility, the URL in Canada was capable of providing many more years of technical and experimental data. Its closure, and subsequent impact on nuclear waste management and disposal research, resulted from programmatic and political pressures, not science and technology. Public affairs and community involvement are essential in any technical program related to nuclear waste disposal. URLs are no exception.

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