Technical Program for Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2013

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R. Crowe, K. Birch, J. Chen, D. Doyle, F. Garisto, M. Gobien, N. Hunt, S. Hirschorn, M. Hobbs, P. Keech, L. Kennell, E. Kremer, P. Maak, J. McKelvie, C. Medri, M. Mielcarek, A. Murchison, A. Parmenter, R. Ross, E. Sykes, T. Yang

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ABSTRACT

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Abstract
This report is a summary of activities and progress in 2013 for the Nuclear Waste Management Organization's (NWMO's) Technical Program. The primary purpose of the Technical Program is to support the implementation of Adaptive Phased Management (APM), Canada's approach for long-term management of used nuclear fuel. Significant technical program achievements in 2013 are summarized below.

- NWMO continued to participate in international research activities associated with the SKB Äspö Hard Rock Laboratory, the Mont Terri Underground Research Laboratory, the Greenland Analogue Project, the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency Research Projects, and the international working group on biosphere modelling (BIOPROTA).

- NWMO provided research contracts and research grants to 12 Canadian universities and colleges, 3 foreign universities and supported 4 postgraduate scholarships in 2013 in collaboration with the Natural Sciences and Engineering Research Council (NSERC) of Canada.

- NWMO's research program published 15 NWMO technical reports and submitted 30 abstracts for presentation at national and international conferences focused on environmental radioactivity and radioactive waste management.

- NWMO continues to pursue engineering conceptual designs, canister and emplacement designs, cost estimates, transportation logistics and implementation schedules in support of APM. In 2013, NWMO designed and fabricated a mobile exhibit trailer featuring an actual used fuel transportation package (*does not contain spent fuel*) to take to communities for public interaction and safety demonstration.

- NWMO continued to develop a repository monitoring and retrieval program, and continued to review developments in used fuel reprocessing and alternative waste management technologies. The NWMO continues to conduct research on used fuel container corrosion, as applicable to the potentially high salinity bedrock of Canada.

- The NWMO geosciences program continued to develop plans and methods for detailed site investigations in both crystalline and sedimentary rock in the fields of: geology, radionuclide transport, microbiology, geomechanics, seismicity, long-term geosphere stability and hydrogeology. NWMO continued to develop and sponsor modelling and analytical methods that will be used to assess long-term geosphere performance. New research programs to develop methodologies for age-dating of minerals within fractures or vein and for the identification of paleoseismic events were initiated.

- NWMO continued to maintain and improve the models and datasets used to support the safety assessment requirements of potential sites and repository designs.

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1. INTRODUCTION

The Nuclear Waste Management Organization (NWMO) is implementing Adaptive Phased Management (APM) for the long-term management of used nuclear fuel, the approach recommended in *"Choosing a Way Forward: The Future Management of Canada's Used Nuclear Fuel"* (NWMO, 2005) and selected by the Government of Canada in June 2007. The APM Technical Program is focused on developing preliminary designs, cost estimates, associated research activities and safety cases for a used fuel deep geological repository (DGR) in order to ensure both continuous improvement and consistency with international best practice. Examples of conceptual designs for a DGR are illustrated in Figure 1.1 and Figure 1.2.

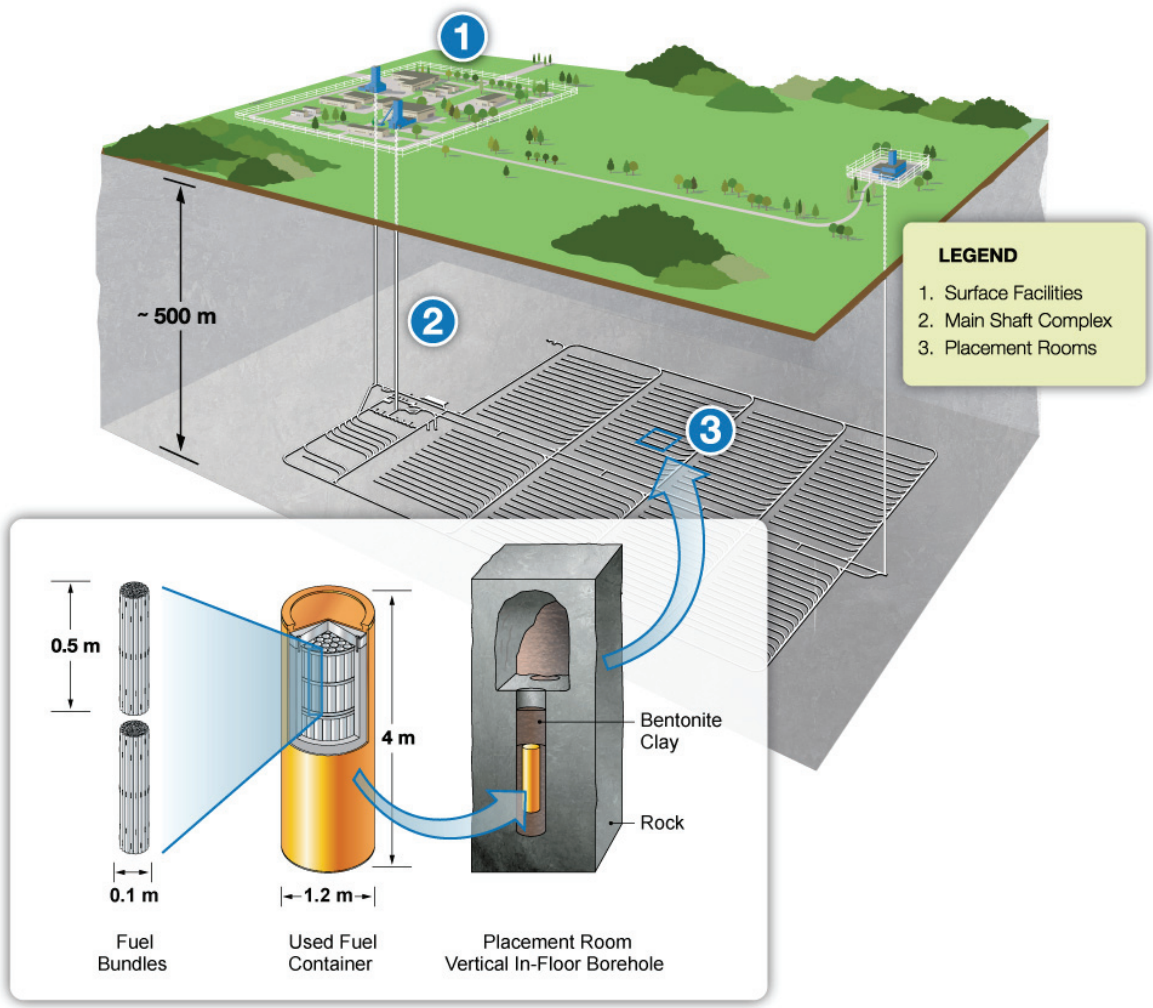


Figure 1.1: Illustration of a Deep Geological Repository – In-floor Borehole Placement

Work conducted and progress made within the APM Technical Program during 2013 is summarized in the remainder of this report. A brief update on the status of NWMO's site selection process is provided below.

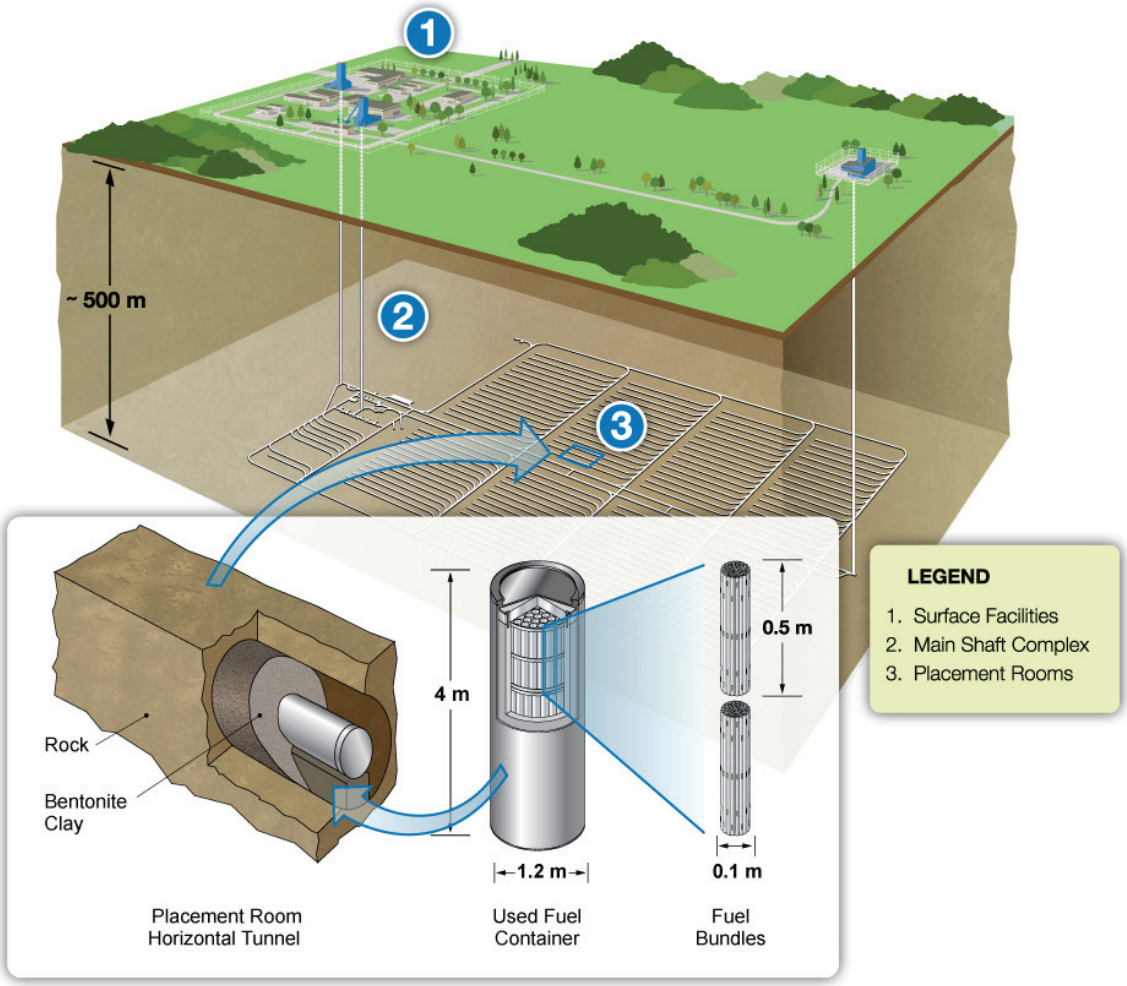


Figure 1.2: Illustration of a Deep Geological Repository – Horizontal Tunnel Placement

1.1 SITE SELECTION PROCESS

On September 30, 2012, the NWMO suspended accepting new expressions of interest from potential host communities. A total of 21 communities passed the initial screenings (Step 2). The suitability of potential candidate sites to safely host a DGR is being evaluated against site selection criteria defined in "*Moving Forward Together: Process for Selecting a Site for Canada's Deep Geological Repository for Used Nuclear Fuel*" (NWMO, 2010). The steps for evaluating the geological suitability of willing and informed host communities consists of the following: a) initial screenings to evaluate the suitability of candidate sites against a list of

preliminary screening criteria, using readily available information; b) feasibility studies to further determine if candidate sites may be suitable for developing a safe used fuel repository; and c) detailed field investigations to confirm suitability of one or more sites based on detailed site evaluation criteria. Each step is designed to evaluate the site in greater detail than the previous step.

NWMO completed initial screenings for ten communities in 2012 and moved on to feasibility studies in preparation for completing all initial screenings in 2013. The initial screening reports are published on NWMO's site selection website (http://www.nwmo.ca/sitingprocess).

In 2013, following the results of these initial screenings, NWMO chose to advance 4 communities to step 3; Ignace, Creighton, Hornepayne and Schreiber and remove 4 communities from the process; Wawa, English River First Nation, Pinehouse and Ear Falls.

2. OVERVIEW OF CANADIAN RESEARCH AND DEVELOPMENT PROGRAM

2.1 REGULATORY FRAMEWORK

Nuclear facilities in Canada, including those for long-term waste management, such as a deep geological repository (DGR), are regulated by the Canadian Nuclear Safety Commission (CNSC) under the *Nuclear Safety and Control Act (NSCA)*. Pursuant to regulations under this *Act*, licences are required from the CNSC for all phases of a nuclear facilities project - site preparation, construction, operation, decommissioning, and abandonment. The CNSC provides additional guidance through regulatory policies, standards and guides.

A facility for long-term management of used fuel is subject to all of the requirements of nuclear safety and security, as well as all safeguards embodied in the *NSCA* and its associated Regulations. Also applicable is the CNSC's Regulatory Policy P-290, *Managing Radioactive Waste,* which states the following principles:

- minimization of waste generation;
- management commensurate with the hazard;
- assessment of future impacts to encompass the time of maximum predicted impact;
- predicted impacts no greater than the impacts that are permissible in Canada at the time of the regulatory decision;
- measures for safe management to be developed, funded and implemented as soon as reasonably practicable; and
- trans-border effects no greater than the effects experienced in Canada.

CNSC's Regulatory Guide, G-320, "*Assessing the Long Term Safety of Radioactive Waste Management",* describes approaches for assessing the potential impact that long-term radioactive waste management methods may have on the environment and on the health and safety of people.

The application for a CNSC licence for a used nuclear fuel DGR would trigger an Environmental Assessment (EA) under the *Canadian Environmental Assessment Act (CEAA)*. Under the CEAA, an EA is required to assess the environmental effects of most projects requiring federal action or decision. Public input will be required at appropriate stages in the EA and licensing process.

As APM is not presently in a licensing stage, the NWMO and CNSC interface is covered by a Special Project Arrangement. Under this arrangement, CNSC is providing pre-project reviews of APM illustrative postclosure safety assessments in representative host formations - one in crystalline rock and one in sedimentary rock.

2.2 APM TECHNICAL PROGRAM OBJECTIVES & OVERVIEW

The primary objective of the APM Technical Program is to complete the preliminary designs, safety cases, cost estimates and research activities for a used fuel deep geological repository in order to support a licence application following planned selection of a preferred site in a 2020 timeframe.

To support the primary objective of the APM Technical Program, the Technical program was comprised of 4 program areas with 7 objectives as listed below.

A: Complete illustrative repository safety assessments

1. Prepare illustrative postclosure safety analyses for reference repository designs in crystalline and sedimentary rock settings.

2. Provide Regulatory Affairs support for CNSC pre-project review of illustrative repository safety analyses, and for APM repository licensing.

B: Optimize repository engineered systems and designs

3. Complete optimization and proof testing of generic repository engineered systems and designs by 2019.

C: Build confidence in the deep geological repository safety case

4. Further increase confidence in the safety case for a DGR.

5. Enhance scientific understanding of processes that may influence DGR safety.

6. Maintain awareness of advances in technology development and alternative methods for long-term management of used nuclear fuel.

D: Provide technical assessment support to APM siting process

7. Conduct geoscientific and biosphere characterization to support selection and licensing of a preferred repository site.

A list of the technical reports produced by NWMO in 2013 is provided in Appendix A.1. Their respective abstracts are provided in Appendix B. All technical reports published before 2000 are listed in Garisto (2000), while the 2000 to 2011 reports are listed in corresponding annual progress reports (Gierszewski et al., 2001, 2002, 2003, 2004; Hobbs et al., 2005, 2006; Russell et al., 2007; Birch et al., 2008, Kremer et al., 2009, McKelvie et al., 2010, 2011, Kennell et al., 2012, Crowe et al., 2013). Appendix A.2 provides a list of the publications and presentations made by APM Technical Program staff and contractors. Appendix A.3 provides a list of graduate students awarded industrial postgraduate scholarships. Appendix A.4 provides a list of the primary external contractors and collaborators for the technical work programs.

2.3 SUMMARY OF INTERNATIONAL ACTIVITIES

An important aspect of the NWMO's technical program is collaboration and interaction with national radioactive waste management organizations in other countries. The NWMO has formal agreements with SKB (Sweden), POSIVA (Finland), NAGRA (Switzerland) and ANDRA (France) to exchange information arising from their respective programs on nuclear waste management. These countries are developing used fuel repository concepts that are similar to

the Canadian concept, and their programs are advanced with respect to repository siting, design development and regulatory approvals.

Since 2004, NWMO has been participating in experiments associated with the SKB Äspö Hard Rock Laboratory (HRL) in Sweden. The purpose of this participation is to improve our understanding of key processes in a repository in crystalline rock through involvement in large-scale projects. NWMO's involvement facilitates collaboration and the sharing of lessons learned in repository technology development and site characterization. In 2013, NWMO continued to participate in the following work programs at the Äspö HRL:

- LASGIT (LArge Scale Gas Injection Test), and
- Engineered Barrier System Modelling Task Force.

Since 2008 NWMO has also been a partner in the Mont Terri Project, which consists of a series of experiments carried out in the Mont Terri Underground Research Laboratory (URL) in Switzerland. The experiments being conducted at Mont Terri are relevant to NWMO site characterization, engineering and safety assessment for sedimentary rock formations. Involvement in the Mont Terri Project allows NWMO to participate in state-of-science research in collaboration with 14 international project partners, including several waste management agencies. During the current phase of the Mont Terri Project, NWMO is involved in the following experiments:

- Disturbances, Diffusion, Perturbation and Retention (DR-A);
- Long-term Diffusion (DR-B);
- Gas Path Through Host Rock and Along Seals (HG-A);
- Hydrogen Transfer (HT);
- Microbial Activity (MA)
- Iron Corrosion in Opalinus Clay (IC);
- Iron Corrosion – Bentonite (IC-A);
- Long-term Monitoring of Pore-pressures (LP);
- Determination of Stress (DS);
- Deep Borehole Experiment (DB);
- Porewater Characterization – Benchmarking and Aquifer Interface Investigation (DB-A); and
- Full Scale Emplacement Experiment (FE-B).

To advance the understanding of the impact of glacial processes on the long-term performance of a DGR, the Greenland Analogue Project (GAP), a four-year field and modelling study of a land-terminating portion of the Greenland ice sheet (2009-2012), located near Kangerlussuaq (Russell Glacier), was established collaboratively by SKB, POSIVA and NWMO. The main objective is to improve the understanding of processes related to groundwater flow and water chemistry adjacent to a continental ice sheet. The Greenland ice sheet is considered to be an analogue of the conditions that are expected to prevail in Canada and Fennoscandinavia during future glacial cycles. In 2012, the fourth and final full season of the GAP project was completed, which included a geochemical sampling program of surface water bodies and a pingo. Radar surveys, and the drilling of boreholes through the ice to the ice-bed interface, concluded in 2012. Planning is underway for comprehensive final reporting, detailing the results of the four-year field campaign and the associated data and modelling interpretations. Final reports (Volume 1 and 2) are projected for publication in 2014-2015.

NWMO continued to participate in the international radioactive waste management program of the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA). Members of this group include all the major nuclear energy countries, including waste owners and regulators. NWMO participated in the following NEA activities:

- Working Group on the Characterization, the Understanding and the Performance of Argillaceous Rocks as Repository Host Formations (i.e., Clay Club) Annual Meeting;
- Integration Group for the Safety Case (IGSC) Annual Meeting;
- Safety Case Symposium;
- Thermodynamic/Sorption Database Development Project;
- IGSC FEP Database Project
- Radioactive Waste Management Committee (RWMC);
- RWMC Reversibility & Retrievability Project; and
- Preservation of Records, Knowledge and Memory Project.

NWMO continued its participation in BIOPROTA, the international working group on biosphere modelling. For 2013, the NWMO is contributing to the funding of three projects, in partnership with other waste management organizations:

- C-14 Project,
- Non-Human Biota Temporal and Spatial Scales Project, and
- Geosphere-Biosphere Interface Project.

2.4 INDEPENDENT PEER REVIEW

The APM Technical Program is reviewed annually by the Independent Technical Review Group (ITRG). In September 2013, the ITRG held their fifth meeting with the NWMO. They reported their findings and recommendations to the NWMO Board of Directors in November 2013. The ITRG 2013 Report and associated NWMO Action Plan can be found on the NWMO website at http://www.nwmo.ca/itrg.

3. REPOSITORY ENGINEERING

Research and development progressed in the Repository Engineering program during 2013. Primary areas of work included: used fuel recovery and transport, used fuel container design, fabrication and corrosion tests, buffer and sealing systems, development of the used fuel encapsulation plant and repository layouts. Summaries of these activities are provided in the following sections.

3.1 USED FUEL RECOVERY AND TRANSPORT

3.1.1 Certification of the Used Fuel Transportation Package

The Used Fuel Transportation Package (UFTP) design was originally certified as a Type B(U) package by the Canadian Nuclear Safety Commission in the 1980s. In 2013, NWMO acquired the UFTP and applied for certification using current CNSC standards. The Safety Analysis Report, drawings, design requirements and engineering standards were revised to accommodate the new standards. The UFTP received a certificate (CDN/2052/B(U)-96) in July 2013 for both road and railroad use.

3.1.2 Mobile Exhibit Trailer for the Used Fuel Transportation Package (UFTP)

In order to demonstrate the robustness of the transportation package, NWMO designed and fabricated a mobile exhibit trailer featuring an actual UFTP. The trailer was commissioned in April 2013 and had nearly 1000 visitors in the first six months of the exhibit. The trailer was designed to meet Transport Canada requirements to transport used nuclear fuel. This level of construction and quality was incorporated into the mobile exhibit trailer in order to provide opportunity for the public to physically see and touch the components and to demonstrate the level of safety that is incorporated into all equipment associated with the transportation of used fuel.

3.1.3 International Analysis of Severe Transportation Accidents

In 2013, the NWMO, as part of its on-going commitment to Adaptive Phased Management, reviewed current international activities related to the predicted performance of licensed Type B transportation packages during real world accidents leading to severe and long duration fires. Since the Baltimore Tunnel Fire and the Fukushima Daiichi nuclear disaster, there has been an interest in analyzing the predicted performance of licensed Type B transportation packages under accident scenarios that are beyond design basis.

Three observations were made as part of the NWMO's review of international studies:

1. The World Nuclear Transport Institute (WNTI) and the International Atomic Energy Agency (IAEA) routinely review the test standards used to license Type B transportation packages to ensure they bound real world experience and meet international safety transportation objectives. WNTI took up the topic during their July 2013 meeting and found the current performance standards and country specific regulations bounded real

world experience. IAEA will take up the same topic during their annual Winter Meeting in 2014.

2. The United States and France had specific requests from special advisory panels for additional research. The US studies were conducted by the US Nuclear Regulatory Commission at the request of the National Academies of Science and the Blue Ribbon Committee on America's Nuclear Future. France and AREVA implemented protocols to address the concern that a loaded Type B package would pass another dangerous goods train in a tunnel. Train operations were modified to prevent shipments of used fuel from occupying a tunnel at the same time as another dangerous goods train. (WNTI, 2013)

3. The US studies determined that the IAEA Type B transportation package fire testing standards were a good predictor of the performance of a licensed package during a real world severe fire accident.

3.2 USED FUEL CONTAINER (UFC)

3.2.1 Used Fuel Container Development

The Repository Engineering program continues to maintain investigations into alternative Used Fuel Container (UFC) designs, including steel only, dual-vessel copper and steel, and a novel copper coated steel container. In 2013, the latter two concepts were further developed; these UFCs are known as Mark I and Mark II.

The Mark I UFC is a large capacity (36 bundle/layer x 8 layer = 288 bundles) vessel based on the SKB/POSIVA KBS-3 dual–shell canister concept, as shown in Figure 3.1. It consists of a steel inner core (with a bolted lid) for structural strength, and a heavy wall wrought copper outer shell that is fully sealed by friction stir welding for corrosion resistance. The basis for the selection of the 288 bundle capacity is that it permits the use of a copper outer shell that is identical to the KBS-3 design. This facilitates a collaborative transfer of demonstrated SKB and POSIVA technology, including analysis and experimental data related to copper overpack supply and assembly, encapsulation plant manufacturing (circumferential friction stir or electron beam welding) and non-destructive examination. A steel only version of the Mark I container is also being developed.

The Mark II UFC is a novel container concept, optimized for Canada's unique CANDU fuel, and is shown in Figure 3.1. It is a mid-sized capacity (12 bundle/layer x 4 layers = 48 bundles) vessel that incorporates a steel core for structural strength and a 3 mm exterior copper coating for corrosion resistance. The weight of the container loaded with fuel is approximately 2,800 kg, approximately 10% of the Mark I design.

The selection of the 48 bundle vessel is based on the results of a manufacturing sizing study, which identified this design as the optimal mid-sized container in terms of manufacturability. This container design permits the use of readily available, standard nuclear-grade pipe size and formed heads from flat plate, instead of a custom forged product. This container size also facilitates automated production in component fabrication, simplifies encapsulation plant operations, and allows buffer pre-assembly in the encapsulation plant.

The design features unique to the Mark II UFC are listed below.

- Hemispherical heads for optimization of stress distributions.
- Hybrid Laser Arc Weld (HLAW) technology to seal the container.
- Corrosion barrier (copper coating) thickness set by the corrosion allowance requirements only and not by manufacturing limitations, which is the case for the Mark I copper shell. The thickness can be tailored to site-specific data.
- A smaller container may allow easier handling and potential use of standard size industrial equipment during manufacture (e.g., forklifts, cranes, etc.).

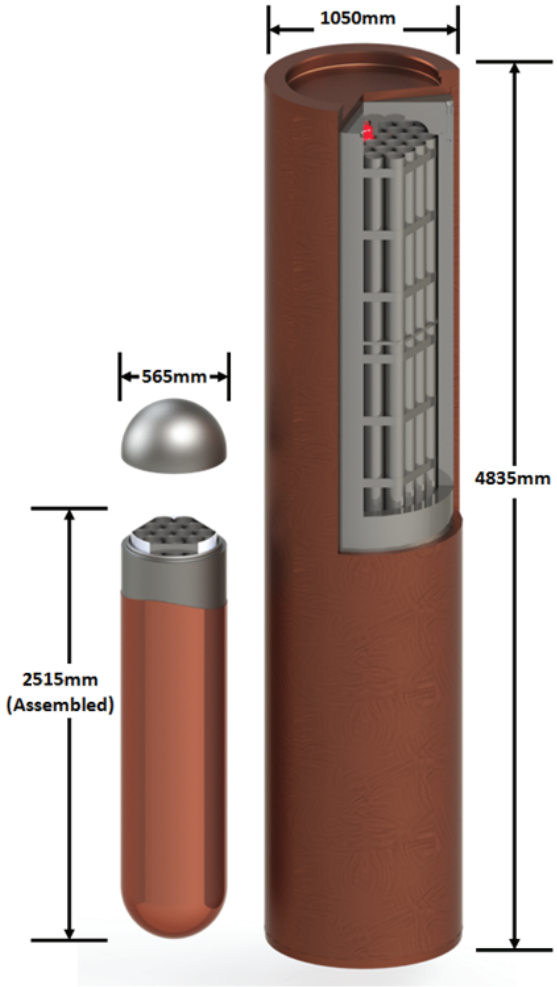


Figure 3.1: Mark II, 48-bundle (left) and Mark I, 288-bundle (right) Used Fuel Containers

In 2013, the NWMO launched several development programs for the Mark I and II containers, focusing on the closure weld, copper coating and corrosion properties. The preliminary results of these programs are outlined in the following sections.

3.2.2 Used Fuel Container Corrosion Studies

3.2.2.1 Corrosion of Copper in Saline Environments

Copper has been identified previously by NWMO and other organizations as a very long-lived metal within the DGR environment. NWMO maintains an active program, particularly in the area of copper corrosion in potentially highly saline groundwater/porewater environments. Such conditions are consistent with water chemistry in many Canadian sedimentary or deep crystalline geological structures. Under the expected salinity (> 3 mol/L) and temperature (up to 100°C), copper will establish equilibrium in anaerobic (i.e., oxygen-free) conditions, via equation [i]:

$$Cu + nCl^- + H_2O \rightleftharpoons CuCl_n^{(1-n)} + \tfrac{1}{2}H_2 + OH^- \qquad \text{[i]}$$

for n = 2, 3.

Calculations regarding such equilibrium suggest that unreacted copper is thermodynamically favourable, but not the corrosion products. This implies an absence of net corrosion upon the formation of a very small amount of hydroxide (OH^-), hydrogen (H_2) and anionic copper ($CuCl_2^-$ or $CuCl_3^{2-}$). Regarding the copper-containing products, greater than 80% of the species above 2.5 mol/L chloride exist in the form $CuCl_3^{2-}$, according to NWMO and University of Toronto calculations, which would be mobile in solution.

For a non-equilibrium system, the continuous movement of hydroxide, hydrogen and anionic copper species away from a corroding copper substrate could favour the forward direction of [i]. Within a repository, of course, such processes are significantly restricted by the repository buffers/clays, as extremely slow diffusion limits movement. With experimental participation of the University of Toronto, NWMO has been striving to identify the maximum rate at which the forward reaction can occur to generate a bounding value for corrosion (i.e., where hydroxide, hydrogen and anionic copper can freely dissipate, unlike in a repository).

As part of the on-going work, which involves very sensitive hydrogen measurements over several months, hydrogen is released very slowly. Corrosion rates on the order of 2-4 nm/y are measured at temperatures above 75°C, in the pH range of 6 to 8 and at 5 mol/L chloride. Rates were slightly higher (2-6 nm/y) at pH ~4-5. At 50°C, corrosion rates were between 0.2 and 0.6 nm/y for pH 4-9. Decreasing the temperature to near room temperature (20-30°C) reduced hydrogen generation to below the detection limit, which is approximately a factor of 10 below the measured values (0.2 nm/y).

As indicated above, these values are all calculated in the absence of clay barriers and bedrock associated with the geosphere, which would act to restrict movement of water toward, and movement of corrosion products away from, the container. Nonetheless, a corrosion rate of 4 nm/y can be conservatively applied to the first 100,000 years, at which time ambient temperatures will be reached. This would result in 0.4 mm of copper loss via corrosion, and actual corrosion would be expected to be significantly reduced in a repository.

3.2.2.2 Corrosion of Copper in Pure Water

Evidence has been presented by Swedish researchers indicating that copper corrosion may proceed for extended periods of time in pure water in the absence of oxygen, as per equation [ii], to produce a copper hydroxide-containing species, as well as hydrogen gas:

$$Cu + H_2O \rightarrow CuOH_n^{(1-n)} + \tfrac{1}{2}H_2 \qquad \text{[ii]}$$

Unlike the equilibrium described in equation [i], the copper hydroxide species proposed by the Swedish researchers (Szakálos et al., 2007) is not expected by conventional thermodynamic analyses. Nonetheless, NWMO has initiated experiments that are comparable to the high salinity copper corrosion experiments described above in order to assess corrosion of copper in pure water. University of Toronto results indicate that very small quantities of hydrogen are evolved from the copper, much lower than the amounts expected from within the high chloride solutions. Equivalent corrosion rates are 0.8 nm/y for experiments conducted at 75°C; experiments at lower temperatures do not produce detectable amounts of hydrogen. As per the measurements in chloride, experiments are designed to monitor the forward reaction by removing hydrogen. Suppression of this reaction, by reaching equilibrium hydrogen partial pressures, is not possible. Because the reaction rate is a factor of 5 lower than those observed where chloride is present, the NWMO copper corrosion allowance will readily account for processes described by both equations [i] and [ii].

3.2.2.3 Corrosion Testing of Copper Coatings

Prior to their implementation as corrosion barriers, copper coatings must be demonstrated as performing equivalently, or better than, conventional wrought copper specimens. NWMO has performed 5 month exposure testing of copper coatings, where oxygen content has ranged from “anoxic” (i.e., experiments conducted in an oxygen-free glove box) to significant (i.e., solutions are purged with air). Electrochemical measurements reveal that the copper coatings behave similarly to the wrought copper specimens, especially when anoxic conditions are utilized. Post-exposure analysis has not resulted in any differentiation among the copper-coated and wrought copper components. For anoxic exposures, (non-corroded) metallic copper can be readily observed for coating and wrought samples. On-going investigations include much longer exposures, as well as exposures of the various samples to humid air, solutions of different salinity and different temperatures. Inter-granular corrosion has been preliminarily investigated through accelerated corrosion tests that do not simulate the DGR environment, but are intended to identify regions within the copper coating that are more susceptible to corrosion processes. No differences in localized corrosion depth can be observed among wrought and coated samples tested in this manner. This work is expected to last until 2016 and will gradually be expanded to include any possible corrosion processes, such as those described for copper in high salinity solutions and in pure water (Section 3.2.2.1).

3.2.2.4 Consequences of Steel Corrosion

For the purposes of gas generation, NWMO has produced a technical report that describes the various stages a steel-only container would pass through, from dry aerobic through saturated and anaerobic periods. Experimental data have been collected and fit into equations, such that

the total corrosion can be calculated as a function of environment and time spent under a given set of conditions.

3.2.2.5 Corrosion of Carbon Steel in Saline Groundwater Solutions

In saline Canadian groundwaters, the performance of steel used fuel containers could be affected. At Western University, a series of long-term exposure tests have been designed to determine the effects of saline groundwater compositions on the corrosion of A516 carbon steel. Three groundwaters were selected for these experiments (Solutions 1 to 3 in Table 3.1). Anaerobic solutions were prepared to minimize the oxygen content of the solutions.

The experiments are being performed in an anaerobic chamber filled with an inert argon atmosphere. A total of sixteen steel coupons are being exposed in each solution. Each specimen was polished to a 1200-SiC grit and left to form an oxide layer for one week prior to exposure to the solution in the anaerobic chamber. Specimens are being removed periodically (from 2 days to 3 years) in order to determine the progress of the corrosion over a three year period. Upon removal, each specimen has been / will be analyzed by a series of surface analytical techniques, including Raman spectroscopy and scanning electron microscopy.

Based on initial results, two additional solutions (Solutions 4 and 5 in Table 3.1) will be used to investigate the effect of carbonate, which appears to control the pH and influence the early stages of the corrosion process (i.e., when traces of oxygen may still be present in solution).

Table 3.1: Solution Compositions Used in Corrosion Experiments

Solution	Analyte Composition	pH Setpoint[1]
1	0.1 M NaCl 0.002213 M $NaHCO_3$	**6.3**
2	SR-270 groundwater (Duro et al. 2010)	**6.3**
3	4.74 M NaCl 0.002213 M $NaHCO_3$	**6.3**
4	4.74 M NaCl 0.1 M $NaHCO_3$	**6.3**
5	4.74 M NaCl 0.002213 M $NaHCO_3$	Unadjusted Initially 6.3

[1]pH adjusted periodically to maintain initial value.

3.2.2.6 Galvanic Coupling between Materials in a Used Fuel Container

In the unlikely event of failure of a used fuel container, groundwater would enter the container, potentially leading to corrosion of the materials in the container. One of the possible types of corrosion would be galvanic, which can occur when two unlike metals are in electrical contact. At Western University, a set of experiments was initiated to investigate the possibility of galvanic corrosion using electrochemical and surface analytical techniques. The potential of the working

electrode (E_g) and the galvanic coupling current (I_g) between pairs of materials were measured. The couples investigated were: Cu and carbon steel (CS), representing the inner and outer layers of the container; CS and Zircaloy-2 representing the inner layer of the container and the fuel cladding; and uranium dioxide (UO_2) and Zircaloy-2 representing the fuel and the cladding. 24-hour long experiments were performed in 3M NaCl solutions. The solutions were purged with O_2 or Ar. For the CS/Cu couple, naturally aerated solution was also used.

For the CS/Cu galvanic couple (in which CS would be the anode), galvanic coupling can take place, producing changes to E_g and I_g, depending on the dissolved oxygen concentration. As expected, maximum values for both parameters were registered in oxygen-saturated solution (see Figure 3.2). Under these conditions, severe corrosion of CS was observed, with the Cu acting as the cathode for O_2 reduction (as well as undergoing some oxygen induced corrosion). Decreasing the O_2 concentration to naturally aerated conditions decreases the total corrosion; however, CS still forms Fe(III)-containing corrosion products. In deaerated solutions, Fe(III) formation is eliminated and the CS showed some localized corrosion without any significant formation of surface deposits. Cu did not show corrosion effects under deaerated and naturally aerated conditions.

For the CS/Zircaloy-2 galvanic couple (CS as the working electrode), the galvanic current is reasonably large under O_2 conditions. In this case, Zircaloy-2 behaves as a protected cathode. The Fe corrosion products formed were similar to those seen with the CS/Cu galvanic couple. In the absence of O_2, the measured corrosion current, I_g, decreases to the order of nanoamps, with Zircaloy-2 exhibiting anodic behaviour. The localized corrosion of CS decreased significantly. SEM images of Zircaloy-2 obtained after coupling with CS do not show any significant corrosion in either O_2 saturated or deaerated solutions.

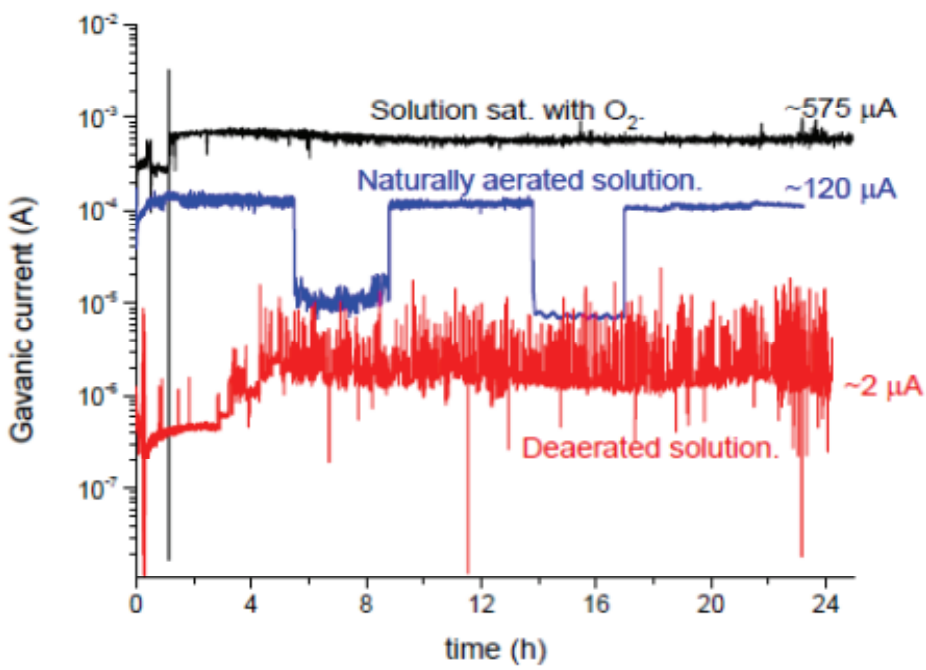


Figure 3.2: Galvanic Current versus Time for the CS/Cu Galvanic Couple

For the UO_2/Zircaloy-2 galvanic couple (Zircaloy-2 as the anode), the measured current indicates that the galvanic coupling current is negligible. In oxygenated solution, it has a value of 55 pA and in deaerated solution, a value of 0.15 pA. The very small values of I_g suggest that no galvanic coupling is taking place.

3.2.3 Used Fuel Container Closure Weld Development

3.2.3.1 Closure Welding of Mark I Steel-only Container

In 2013, a comprehensive study was carried out to investigate the technical feasibility of using narrow-gap gas-tungsten-arc welding (NG-GTAW) for final closure welding of the Mark I steel-only container. The study was conducted by a reputable Canadian engineering company, who is specialized in remote welding applications in radioactive environments. The conclusion of the study is that the NG-GTAW technology can, with high confidence, perform the required closure welding of the Mark I container at the specified production rate in the used fuel encapsulation plant. The most significant unknown in the production cycle is the amount and type of weld rework that may be required. A statistical study is recommended to estimate the required rework.

3.2.3.2 Closure Welding of the Mark II Container

NWMO is investigating two novel welding processes for the final closure of the Mark II UFC. In 2013, extensive welding trials were conducted using Hybrid-Laser-Arc Welding (HLAW) and Friction Stir Welding (FSW) processes. HLAW is a combination of the laser welding processes and the gas-metal-arc welding process. The FSW is a solid state welding process. Metallographic cross sections of HLAW and FSW test welds from the NWMO program are shown in Figure 3.3. The findings of the 2013 study confirm that closure welds can be made with excellent weld quality and mechanical properties using both the HLAW and FSW processes. No heat treatment is required post weld. Closure weld with a weld penetration of > 8 mm can be readily achieved in a single weld pass.

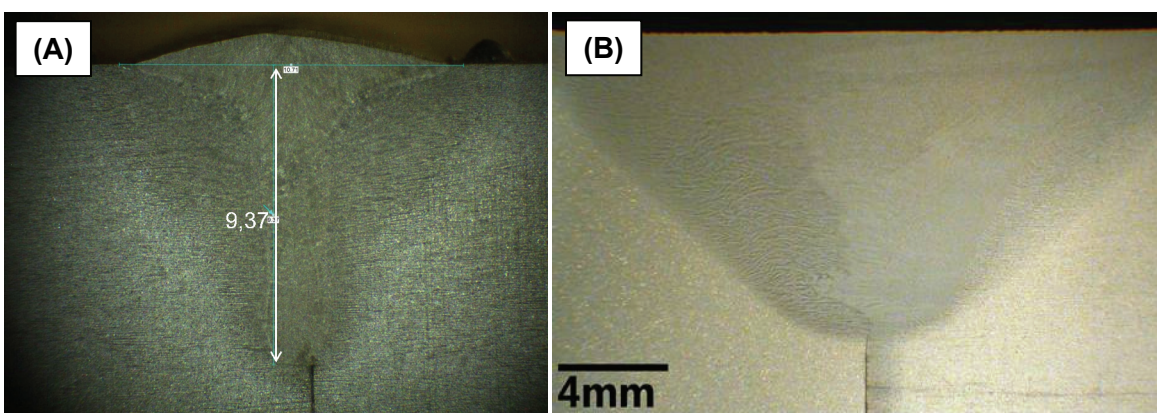


Figure 3.3: As-welded, (a) HLAW Weld Cross-section and (b) Friction Stir Weld (FSW) Cross-section

The HLAW has been selected by NWMO as the reference closure welding process for the Mark II container. A fully automated welding system is essential for the final closure of the repository containers in a radioactive environment at the used fuel encapsulation plant. The closure welding operation can readily be demonstrated using the currently available fully-automated robotic HLAW system.

In 2013, six closure welds meeting nuclear-grade quality acceptance criteria were successfully fabricated in full-size Mark II container mock-ups using a robotic HLAW system (Figure 3.4).

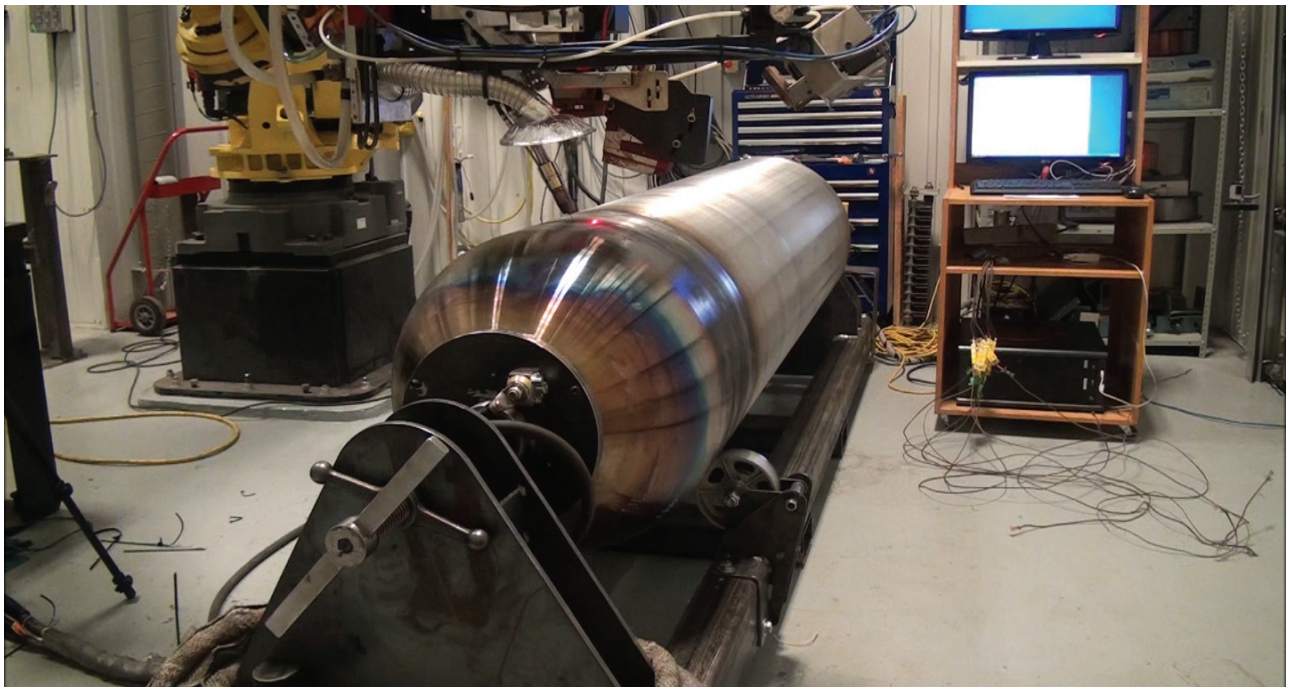


Figure 3.4: Hybrid Laser Arc Welding (HLAW) of Prototype Full-scale Mark II Used Fuel Container

3.2.4 Used Fuel Container Copper Coating Development

3.2.4.1 Electrodeposition

Electrodeposition offers the advantage of commercially available coating production on a large scale. Because it is a relatively slow process, it is often used for thin coatings (< 0.5 mm). However, NWMO and its contractors have been successfully developing 3 mm copper coatings on steel substrates for the previous 2 years. Properties of the coatings include:

- excellent adhesion to the steel via metallurgical bonding;
- no porosity;
- containing no hydrogen or oxygen; and
- high purity.

Among the work conducted in 2013, are small plate sample test coupons, miniature containers (1/8th scale) coated with 3 mm of copper, as well as arc segments from full-sized container cylinders (see Figure 3.5).

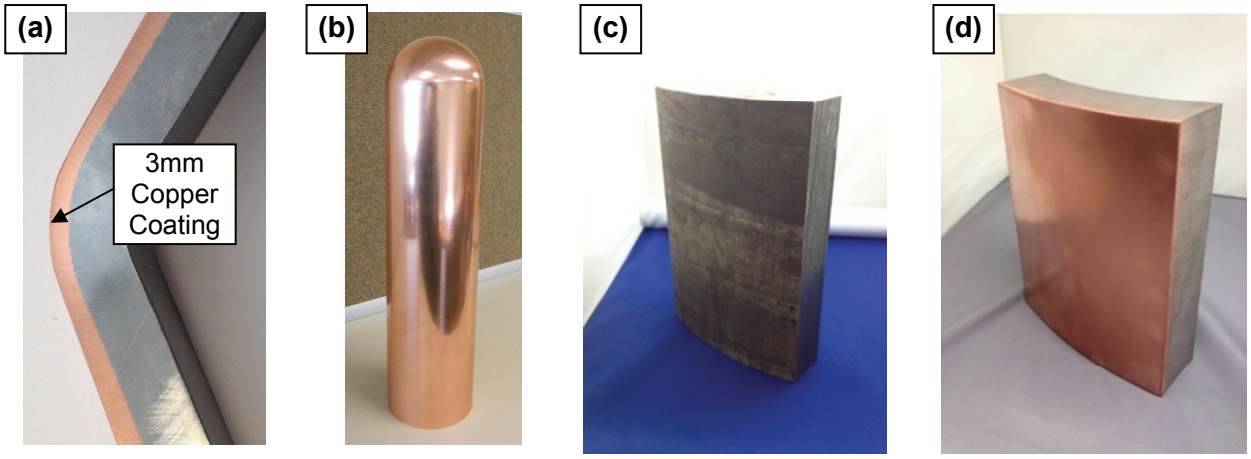


Figure 3.5: Electrodeposited Copper Coating Samples: (a) Plate; (b) 1/8th Scale Container Mock-up; and Full Sized Cylinder Segments (c) Uncoated and (d) Coated

3.2.4.2 Cold Spray

Cold spray involves the acceleration of powders within an inert carrier gas to high velocities. Upon impact on a metal substrate, the powders form with the substrate a metallic layer that mechanically bonds to the substrate. While very high deposition rates can be obtained by a single gun (i.e., up to 1 kg/min), it has been primarily used as a repair process within industry.

Within the NWMO program, cold spray has been investigated for both complete UFC coverage and coverage of the weld zone. Based on 2012 results, NWMO produced coated container mock-up components, and verified that the coating properties are suitable for used fuel containers. Figure 3.6 illustrates 2013 results for 3 mm coatings on 40 mm steel plate, as well as on a “stubby” UFC segment. Machining of copper coating on a prototype full-scale Mark II UFC is illustrated in Figure 3.7.

As can be observed visually, extremely high quality coatings can be readily produced via cold spray. Extended analysis reveals that coatings have very low porosity (< 1%), and are bonded to steel substrates extremely well (> 60 MPa adhesive strength via ASTM test methods). On-going work is focusing on the development of cold spray coatings for the closure weld zone.

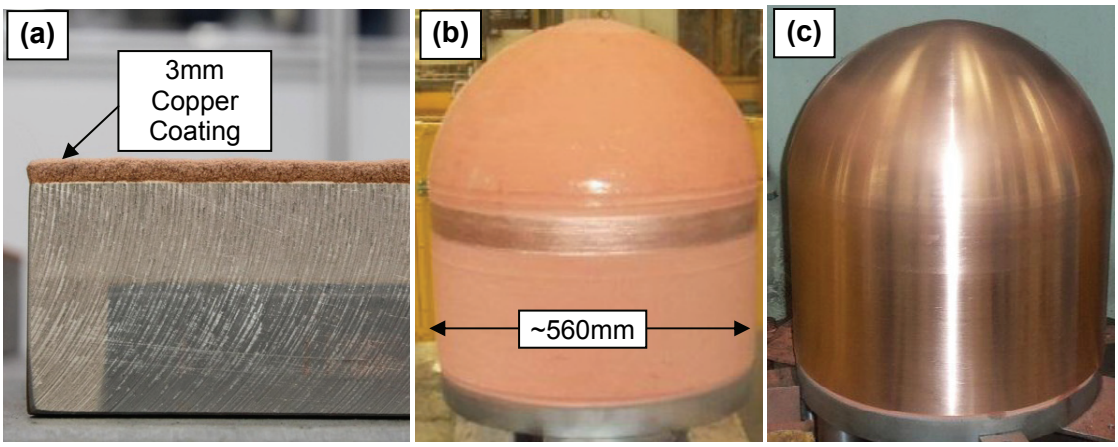


Figure 3.6: Cold Spray Copper Coating Samples (a) Plate (b) Container Mock-up (as-deposited) and (c) Container Mock-up (post-machining)

Figure 3.7: Machining of Copper Coating on Prototype Full-scale Mark II Used Fuel Container

3.2.4.3 Copper Weld Overlay

A scoping study was carried out in 2013 at Conestoga College to investigate the technical feasibility of fabricating sound copper weld overlay onto the steel substrate of a used fuel container utilizing copper-wire laser welding (CWLW), gas-tungsten-arc welding (GTAW) and gas-metal-arc welding (GMAW). The preliminary weld overlay samples were evaluated using metallurgical examination, micro-hardness tests, side bend tests and ultrasonic inspection. All three copper weld overlay processes display satisfactory fusion and sound metallurgical bonding and quality, and are all suitable for remote application in a radioactive environment. At this stage, it appears that GTAW is the most promising method for fabricating high quality copper weld overlay, partly because the GTAW process can be applied for repairing defects in the copper weld overlay. Work will continue in 2014 to further assess GTAW.

3.2.4.4 Non-Destructive Examination (NDE) of Copper Coatings

As part of the coating development program, the NWMO has initiated a Non-Destructive Examination (NDE) program to assess coating integrity. Since 2012, results demonstrated that cold spray and electrodeposited samples are inspectable. The 2013 focus was on weld overlay samples, particularly because weld overlay methods can produce coarse grained particles that are more difficult to inspect. NDE experts, from Eclipse Scientific, determined that defects greater than 0.8 mm are readily detectable by a combination of Eddy Current, Eddy Current Array, Phased Array Ultrasonic and conventional Ultrasonic Testing for all weld clad samples. Among the samples, GTAW was the most readily inspectable (i.e., the lowest background noise) regarding bond strength. These results give a solid bounding case for NDE examination criteria and on-going work will assess whether or not smaller defects can be identified.

3.3 USED FUEL ENCAPSULATION PLANT

3.3.1 Encapsulation Plant Throughput Study

The NWMO undertook a study to assess what changes would be required to the encapsulation plant in order to process a 48-bundle capacity used fuel container while maintaining the throughput requirement of 120,000 used fuel bundles per year.

ATS Automation was selected to perform this study, which focused on: 1) review of the plant process requirements and 2) development of a conceptual plant for a 48-bundle capacity used fuel container. ATS based the study on a conceptual plant design that employs a modular approach with multiple, independent work cells to achieve the throughput target of 10 containers per day. The proposed plant meets the 120,000 bundles per year requirement. The flexible and adaptive plant design and modular work cell approach minimizes the impact of upset conditions (e.g., equipment failures that impact fuel transfer and/or NDE processes) on plant throughput.

The study was based on current technologies and proven industrial systems. The findings support that the throughput is achievable with the 48-bundle container. It was confirmed that the plant could be configured to achieve the 120,000 bundles per year net throughput while considering moderate levels of system availability.

3.4 BUFFER AND SEALING SYSTEMS

In 2013, NWMO continued to assess the properties of bentonite-based sealing materials through consolidation and triaxial testing studies. The bentonite-based sealing materials that currently are being evaluated for use in a DGR are listed below.

- Highly Compacted Bentonite (HCB) – 100% bentonite clay;
- Bentonite-Sand Buffer (BSB) – 50% bentonite and 50% sand by mass;
- Dense Backfill (DBF) – 70% crushed granite, 25% lake clay and 5% bentonite by mass;
- 70/30 Bentonite Sand (70/30BF) – 70% bentonite and 30% sand by mass;
- Light Backfill (LBF) – 50% bentonite and 50% crushed granite by mass; and,
- Gap Fill (GF) – 100% bentonite clay fabricated in the form of dense pellets.

In 2013, a long-term triaxial testing and consolidation program continued to assess the properties of a 70/30 bentonite sand mix (70/30BF). This work is underway in the geotechnical laboratories of both the Royal Military College of Canada and the University of British Columbia.

3.4.1 Microbial Studies of Repository Sealing Systems

The NWMO near-field microbiology program assesses the presence and diversity of microorganisms in the engineered barrier system (EBS), with the objective of demonstrating that highly compacted bentonite will inhibit microbial activity. The work is organized into microbiological, geochemical and modelling activities that together will provide evidence that microbiologically influenced corrosion will not compromise the used nuclear fuel container.

The microbiology work program is being conducted collaboratively between researchers at the University of Saskatchewan and Ryerson University. The specific program objectives are to: 1) explore the potential for biofilm presence and activity in interfaces between repository components, with emphasis on the host rock-bentonite interface; and 2) assess the presence and activity of sulphate-reducing bacteria in highly compacted bentonite under anaerobic conditions. Activities in 2013 focused on identifying microorganisms that are naturally present in MX-80 bentonite and developing experimental methodologies that will be used in support of the project objectives.

Because organic carbon is a requirement for heterotrophic bacteria, the main objectives of the geochemistry work program with the University of Toronto were to: 1) conduct a state of science review of natural organic matter (NOM) in the deep subsurface and bentonite clays; and 2) evaluate NOM in bentonite clays using advanced molecular techniques. The state of science review recommended that high-resolution molecular level techniques be used to characterize NOM in bentonite clays under consideration for use in a DGR. As such, gas chromatography, coupled with mass spectrometry and nuclear magnetic resonance spectroscopy, was used to evaluate the structure and composition of NOM in several bentonite clays. The composition of NOM in the clays at the molecular-level did not seem to vary much between the different clays evaluated and showed signs of having already undergone substantial degradation. Furthermore, the type of NOM found is considered to be more recalcitrant compared to other

labile NOM sources (sugars, proteins, and small organic acids), which were not detected. The results will be detailed in two 2014 NWMO technical reports.

In 2013, the modelling work program with the University of Toronto developed methodologies to assess limiting nutrients in the DGR and estimate the maximum biomass that could conservatively be supported. In addition, a review of existing numerical models used by the nuclear agencies around the world for microbiologically influenced corrosion modelling was carried out. The review focused on reactive-transport, corrosion, and gas generation models and assessed their capability to simulate different processes that would affect corrosion of used fuel canisters. On the basis of the review, it was recommended that a new Canadian model for microbial processes in a deep geological repository (DGR) be developed using COMSOL as a platform. Activities in 2014 will be focused on the development of the new model.

3.5 SITE AND REPOSITORY

The NWMO continued to support the development of underground placement for both the Mark I and Mark II Used Fuel Containers in crystalline and sedimentary rock. In 2013, conceptual placement room designs were optimized, as shown in Table 3.2: Summary of Mark I and Mark II Placement Concepts, so that the surface temperature of the UFCs did not exceed 100°C. The reference placement concept for the Mark I Used Fuel Container is based on the concepts for the IV-360 UFC (SNC-Lavalin Nuclear, 2011a, 2011b), as shown in Figure 3.8a and Figure 3.8b. For the Mark II concept, the used fuel container will be surrounded by a highly compacted bentonite overpack. The resulting “Buffer Box” would be assembled in the used fuel packaging plant, and then transported underground to the placement room. In this concept, the placement room is a drill and blast excavated opening that has a slightly larger cross-sectional area than the two transversely stacked Buffer Boxes. An illustration of the placement of the Buffer Boxes is shown in Figure 3.8c.

Table 3.2: Summary of Mark I and Mark II Placement Concepts

Used Fuel Container	Geosphere	Placement Method	Container spacing (m)	Geometry of Excavation
Mark I (288 bundle)	Crystalline	In-floor Borehole	4.2	1.75 m diameter, 7.9 m deep In-floor borehole
Mark I (288 bundle)	Sedimentary	Horizontal Tunnel	8	2.05 m diameter, Horizontal Tunnel Placement
Mark II (48-Bundle)	Crystalline	In-room Concept	1.47 m (each lift)	Rectangular (2.1 m high by 3.0 m wide) – transversely loaded UFC
Mark II (48-Bundle)	Sedimentary	In-room Concept	1.72 (each lift)	Rectangular (2.1 m high by 3.0 m wide) transversely loaded UFC

Note: Room spacing set at 20 m for all placement methods

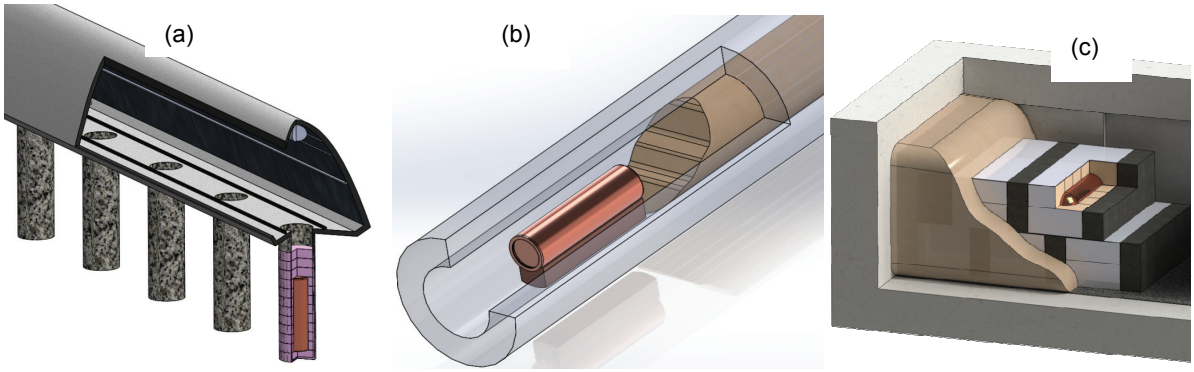


Figure 3.8: Illustrations for (a) In-floor Borehole, (b) Horizontal Tunnel and (c) In-room Concept

4. GEOSCIENCE

In collaboration with technical experts, both in Canada and internationally, the NWMO is pursuing an active geosciences research program addressing a wide range of topics related to the development of DGRs for used nuclear fuel. The primary objectives of the NWMO's geosciences technical program are to: 1) ensure preparedness to perform site characterization activities in evaluation of candidate site suitability for DGR implementation (sedimentary and crystalline settings); and 2) advance the understanding of repository geosphere evolution with respect to stability and resilience, as relevant to the development of a DGR Safety Case. These objectives are achieved through a multidisciplinary approach involving the coordinated effort of research groups drawn from Canadian universities, consultants, federal organizations and international research institutions. The following sections outline key NWMO Geoscience activities in 2013.

4.1 GEOSCIENTIFIC SITE CHARACTERIZATION – SITE-SCALE

4.1.1 Microbiology Site Characterization Methods

In 2013, research activities have focused on the development of techniques for the characterization of potential indigenous microbial communities in low-permeability sedimentary rock using core samples of shale, interbedded shale and limestone, argillaceous dolostone and argillaceous limestone. To circumvent intrinsic properties of these cores (e.g., low biomass and high salinity/clay content), extensive methods development and control comparisons were undertaken using biomarker (PLFA analysis) and molecular genetic (DNA extraction and aggressive PCR amplification) approaches (Slater et al., 2013). Importantly, during sample collection and analysis, potential sources of contamination were carefully characterized and pristine interior subsamples of core were used for the extractions and analysis.

The results of this study demonstrate that, if present, microbial biomass is extremely low in these low-permeability materials. Unfortunately, the two primary approaches applied to these samples failed to corroborate one another, as the cell density estimates of 1 to $3x10^5$ cells/gram based on PLFA data are just below the detection limit determined for DNA analysis of $4x10^5$ cells/gram. As such, the DNA results alone can neither confirm nor refute the presence of microbial cells as indicated by the PLFA results. Notably, a similar situation was reported by Stroes-Gascoyne et al. (2007) for the Opalinus clay, where PLFA analysis yielded concentrations greater than those observed in this study, and yet DNA could not be amplified from the samples. Stroes-Gascoyne et al. (2007) proposed that the highly sorptive nature of the clay may be related both to PLFA preservation and to DNA amplification inhibition. In the current study, it is likewise proposed that DNA amplification was inhibited by interference from either mineral or organic components within the host rock. Beyond addressing this specific sample set, the experimental and analytical approach developed for this study represents an effective means to assess low biomass systems and should assist in the development of future site investigation plans with respect to detecting and characterizing life in low-permeability, low biomass environments under consideration for development of a deep geological repository. Activities in 2014 will involve development of methods for extraction and analysis of microorganisms from crystalline rock.

4.1.2 Sorption

Sorption is a potential mechanism for retarding radionuclide transport from a DGR to the environment. NWMO initiated the development of a Canadian sorption database for highly saline groundwaters by conducting a review of the open literature and international sorption databases to find any available data relevant to Canadian sedimentary rocks (shale and limestone) and bentonite for the elements of interest to safety assessment (Vilks, 2011). This initial database has been augmented with sorption data measured experimentally for Canadian sedimentary rocks and bentonite in saline solutions for the elements Cu(II), Ni(II), Pb(II), Eu(III), U(VI) and Zr(IV) using batch sorption tests and long-term mass transport tests (Vilks et al., 2011; Vilks and Miller, 2013), as well as any available literature data. A technical report documenting the updated sorption coefficient values for shale, limestone and bentonite for key elements of interest (i.e., C, Ni, Cu, As, Se, Zr, Nb, Mo, Tc, Pd, Sn, Cs, Eu, Pb, Bi, Ra, Th, Pa, U, Np, Pu and Am) in saline conditions, as derived from experimental values, literature review and sorption modelling, is expected in 2014.

In 2013, a two-year research program in collaboration with Atomic Energy of Canada Limited (AECL) was initiated to further develop the NWMO's database of sorption coefficient values for Canadian sedimentary rocks and bentonite. The sorption database will be further developed by: 1) experimentally measuring sorption coefficients for the elements Cs(I), Pd(II), Sn(IV), Zr(IV) and Th(IV) onto Canadian sedimentary rocks (limestone and shale) and bentonite in a highly saline Na-Ca-Cl solution with TDS of 275 g/L under low O_2 conditions by both batch sorption tests and long-term diffusion tests; 2) performing a comprehensive literature review to find any new sorption data relevant to Canadian sedimentary rocks; and 3) conducting thermodynamic sorption modelling.

In addition, a two-year research program was initiated in 2013 with the Southwest Research Institute to measure the sorption of six key redox-sensitive elements, Se(-II), As(III), Pu(III), U(IV), Tc(IV) and Np(IV), onto Canadian sedimentary rocks (limestone and shale) and bentonite in the highly saline Na-Ca-Cl solution with TDS of 275 g/L under reducing conditions. NWMO's database of sorption coefficient values for these key redox-sensitive elements will be updated with the experimental sorption coefficient values determined in this research program.

A new research program will be initiated in 2014 with McMaster University to study the sorption properties of Np onto shale and illite in highly saline solutions under oxidizing (as Np(V)) and reducing (as NP(IV)) conditions. This research will investigate to what degree sorption coefficients determined for Np on illite can be considered representative of those for shale.

4.1.3 Radiometric Age Determination of Fracture-Infilling Mineral Phases

A key issue associated with determining site suitability relates to an understanding of both site evolution and stability in response to external perturbations on geologic timescales. Mineral-filled fractures and openings (e.g., veins and vugs) preserve evidence of fluid migration in the geologic past. Vein and vug emplacement, for example, may have occurred as a result of diagenesis (in sedimentary rocks), orogenic activity and/or uplift and erosion. Characterization of the infilling mineral phases, including absolute age determinations of the in-filling material, can provide useful information regarding the timing of fracture occurrence and the nature of fracture fluid in the geologic past.

As part of fracture infill mineral studies, the application of radiometric Uranium-Lead (U-Pb) age dating is continuing at the University of Toronto Jack Satterly Geochronology Laboratory. An important component of the work program involves development of a methodology to extract reliable absolute ages of calcite mineral growth using a comparative analysis of Laser Ablation-Inductively Coupled Mass Spectrometry (LA-ICPMS) and Isotope Dilution-Thermal Ionization Mass Spectrometry (ID-TIMS) techniques (Davis, 2013). While this work program is focused on vein calcite in sedimentary rocks, it is envisaged that the methods and interpretative strategy developed will be well suited to crystalline rock environments.

Initial results have demonstrated that the above methodology is capable of yielding reliable ages for fracture infill calcites in Paleozoic age carbonate rock. A technical report, highlighting the results of this successful methodology development work is in the final stages of review, and a new two-year project has been initiated to continue the work program. An effort will be made during this two-year initiative to extend and test the reliability of the method thus far developed on fracture calcites in host rocks of igneous and metamorphic character.

4.1.4 Matrix Porewater Extraction and Geochemical Analysis

In 2013, the NWMO continued to explore the development, refinement and testing of methods to enhance porewater extraction from low permeability rock formations with researchers from the University of Ottawa, the University of New Brunswick and the University of Bern. Porewater is defined as groundwater within the connected pore space between mineral grains in low-permeability rock, which does not flow readily into, and cannot be sampled from, surface-drilled boreholes.

The research programs discussed below aim to develop and refine isotopic and geochemical analysis techniques that can be used in site investigation activities in both sedimentary and crystalline rock. Chemical and isotopic compositions of groundwater and matrix porewater provide information on the origin and evolution of the groundwater flow system and can be used to determine groundwater fate over geologic time frames. In addition, near-field performance, safety assessment and groundwater transport/evolution models require knowledge of groundwater geochemical compositions through use of site-specific analogues.

4.1.4.1 Micro Vacuum-distillation and Crush & Leach (University of Ottawa)

The vacuum-distillation and crush and leach techniques were applied successfully to the pore fluid characterization program for the Ontario Power Generation Low & Intermediate Level Waste (L&ILW) DGR project at the Bruce nuclear site (Clark et al., 2010a, 2010b, 2011). The 2013 work program focused on the continued refinement of the micro vacuum-distillation (μVD) technique, which has been developed, in part, to assess the effects of grain size and the inclusion of clay-bound waters on the results of porewater geochemical analyses. The μVD technique is a closed-system crushing and extraction procedure, designed to minimize potential evaporative losses (see Figure 4.1), in addition to demonstrating advantages over the previous vacuum-distillation method, including: reduced extraction times, more efficient temperature control, smaller sample sizes and rapid analysis of stable water isotopes by cavity ring-down spectroscopy (CRDS).

Further work is planned to evaluate and compare the results of the μVD technique with those from international characterization programs using traditional methods developed for relatively

higher permeability rock. Benchmarking activities, using samples of Opalinus Clay, collected as part of the Mont Terri DB-A program (see Section 4.4.2), are a key component of method testing/evaluation to be performed in 2014. In addition, the potential to adapt the µVD method for application on crystalline rock cores is being investigated.

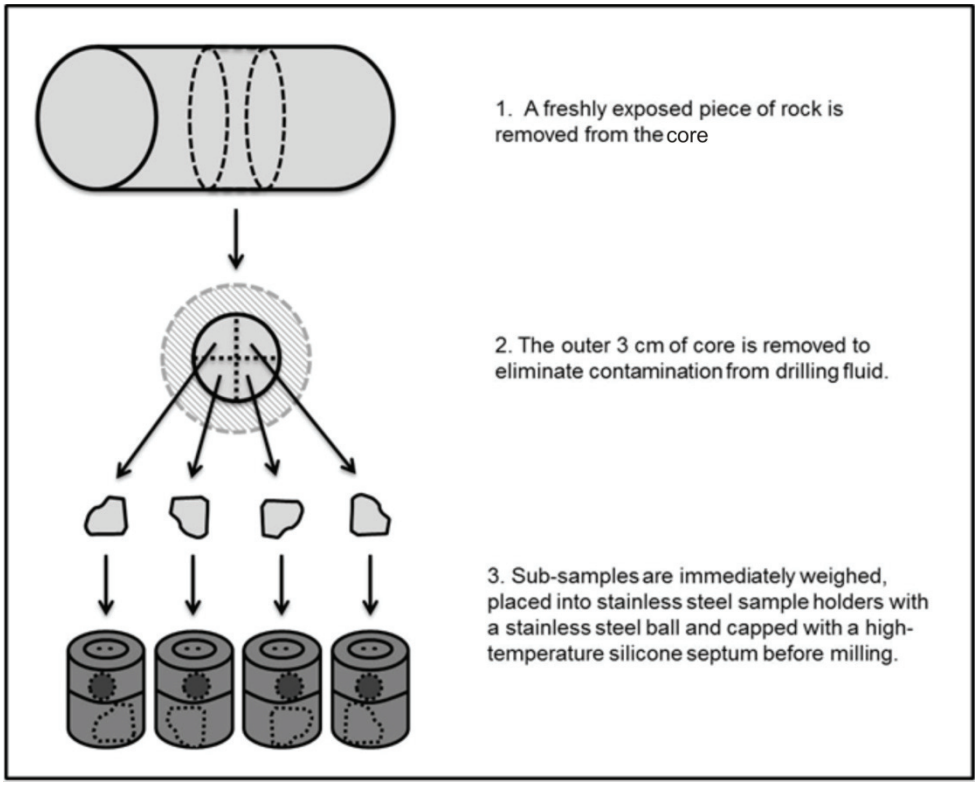


Figure 4.1: Protocol for µVD Sample Preparation

4.1.4.2 Filter Paper (University of New Brunswick)

The filter paper technique uses capillary action to extract porewater into a sheet of low chemical background cellulosic paper sandwiched between two pieces of rock core and left to absorb porewater for an extended period of time (i.e., from weeks to months). Calibration of a Near Infrared (NIR) spectrometer, to allow determination of water mass absorbed by the cellulosic paper, was completed in 2013. Work in 2013 confirmed that: 1) cellulosic sheets are capable of extracting porewater and solutes from low permeability rock formations; 2) solutes can be quantitatively leached from the paper and quantified by Inductively Coupled Plasma Mass Spectrometry (ICP-MS); 3) the mass of porewater extracted can be quantified by NIR spectrometry; and, 4) concentrations of solutes in the porewater can be quantified with acceptable precision and accuracy by combining data for solute mass obtained by ICP-MS and water mass obtained by NIR (see Figure 4.2).

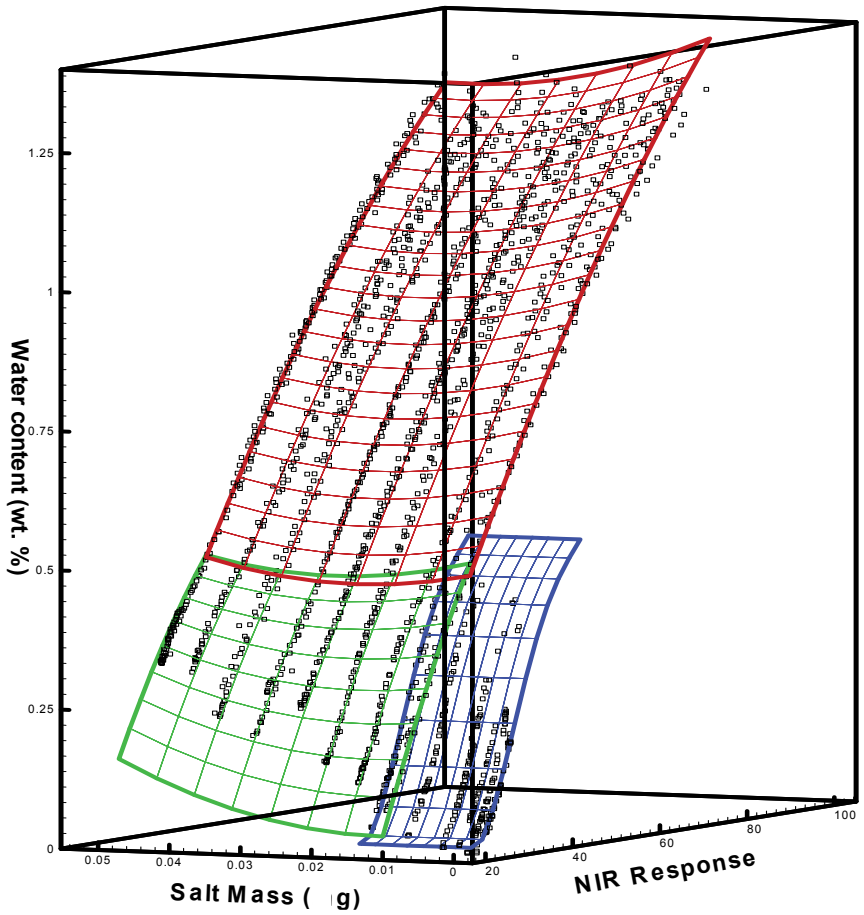


Figure 4.2: NIR Calibration Surface for Cellulosic Paper at a Range of Salt Masses

The technique requires very small volumes of porewater to provide enough solute mass for accurate analysis, and provides a means of quantifying the in-situ composition of the major and minor solutes (Na, K, Ca, Mg, Sr, Cl and Br) in high salinity porewaters without any need for sample dilution, crush and leach, or reliance on measurements of sample porosity, thus reducing uncertainties in the measured porewater compositions by removing potential analytical artefacts. Water content also can be confirmed using gravimetric methods (see Figure 4.3). Testing of the filter paper technique on preserved cores collected at the Bruce nuclear site was initiated in 2013 and results are expected in 2014. Analysis of stable water isotopes (^{18}O and ^{2}H) by CRDS using inert glass filter paper continues to be tested/developed to-date.

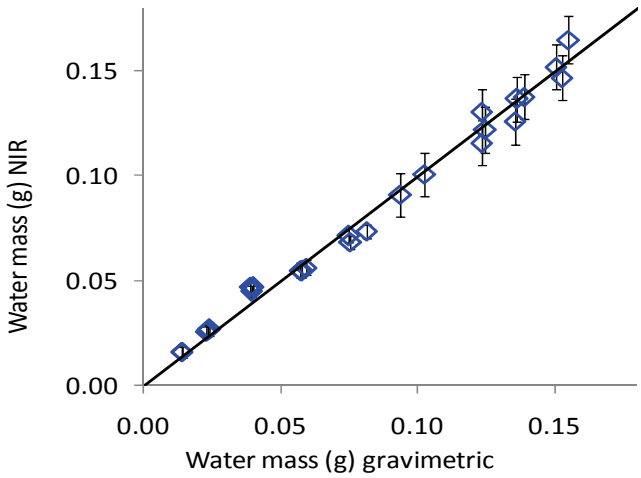


Figure 4.3: Comparison of Water Mass Determined Gravimetrically and by NIR

4.1.4.3 Out-diffusion, Isotope Diffusive Exchange and Squeezing (University of Bern)

Out-diffusion and Isotope Diffusive Exchange

Both the out-diffusion and the isotope diffusive exchange techniques have been tested and evaluated at the University of Bern in the context of extracting and analyzing porewaters from low permeability crystalline rock. The out-diffusion method is based on the concept that the dissolved components within the matrix porewater of a sample can be diffused into an enclosed water reservoir and reach steady-state conditions (i.e., a state of equilibrium between the water and the host rock), and the method has been demonstrated useful in extracting matrix porewater from low porosity (0.003), low permeability ($< 10^{-17}$ m^2) rock. A naturally saturated, intact core is immersed in deionised water for equilibration, which is determined from measurements of chloride concentration at periodic intervals. Periodic sampling results are used to establish a tracer time series and the derivation of transport properties (e.g., D_e).

The isotope diffusive exchange technique is used to determine the stable water isotope signatures of porewater. Saturated rock pieces are equilibrated with a test water of known isotopic composition over a vapour phase, from which porewater $\delta^{18}O$ and $\delta^{2}H$ values are derived by mass balance calculations.

Both of these techniques were demonstrated using four preserved crystalline rock core samples collected as part of the GAP (see Section 4.4.1). The purpose of this work was to demonstrate and to formally document the application of procedures and protocols for the characterization of porewater in crystalline rock cores using both methods. In 2013, out-diffusion experiments using GAP cores – to determine test water and porewater concentrations – were completed, as was the formal NWMO technical report (Eichinger and Waber, 2013). The final report documents: 1) the results of method demonstration and evaluation; 2) essential experimental and sample handling procedures; and 3) laboratory protocols to determine porewater chemistry and evaluate potential analytical artefacts.

Squeezing

Evaluation and application of the squeezing technique has been performed at the CRIEPI Laboratory in Japan in collaboration with the University of Bern (see squeezing system schematic in Figure 4.4). As part of the work program, three low-permeability core samples collected from the Salina F Unit, the Georgian Bay Formation and the Blue Mountain Formation shales during site characterization activities at the Bruce nuclear site were tested. The squeezing technique was capable of extracting water from the Blue Mountain Formation samples only, at the maximum pressure of 500 MPa, while no water was obtained from either the Salina F Unit or the Georgian Bay Formation shale. The fluid underwent geochemical analysis (Ion Chromatography) and porewater content determinations at the University of Bern in 2012 and, in 2013, a method to perform isotopic analysis for $\delta^{18}O$ and $\delta^{2}H$ using CRDS was tested and utilized on the single porewater sample extracted from the Blue Mountain Formation. The final report, documenting the challenges and successes, as well as the experimental protocols and procedures, was completed for the NWMO in 2013 (Mazurek et al., 2013).

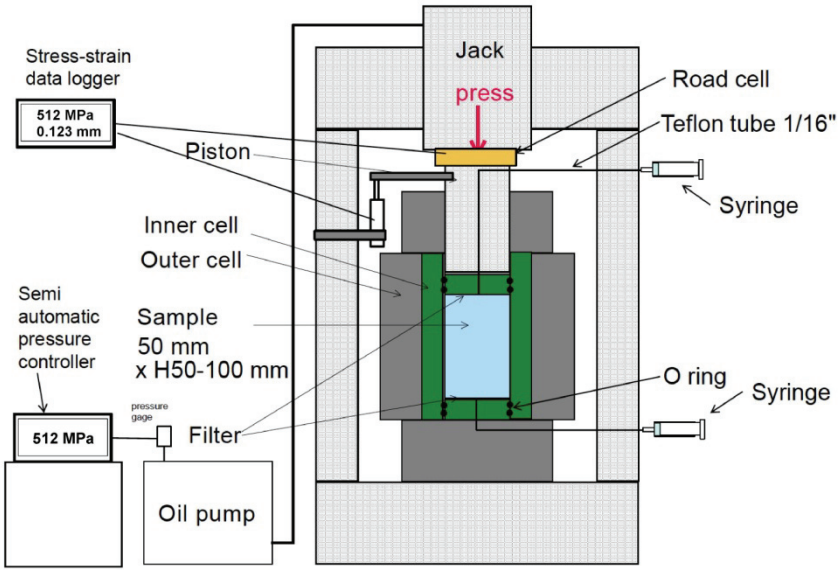


Figure 4.4: Schematic of CRIEPI's Squeezing Rig

4.1.4.4 Review of Porewater Extraction Methods (University of Western Ontario)

A technical independent review of the current porewater extraction methods adapted for use in sedimentary rock was initiated with the University of Western Ontario and is anticipated to be complete early in 2014. The review is designed to allow for the critical evaluation of methodologies (i.e., micro vacuum-distillation – including crush and leach; and diffusive exchange – for application to sedimentary rocks containing highly saline porewaters) that are currently being developed and/or refined for use in APM. Thus far, the review has provided the Geosciences Applied Research Program, and participating researchers, with feedback on the

effectiveness and reliability of current experimental methodologies, as well as recommendations for improvement.

4.1.5 Diffusion

Diffusion is considered to be the dominant mechanism for solute transport in low permeability geological formations. An X-ray radiography technique has been successfully developed, in collaboration with the University of New Brunswick, to quantify diffusion coefficients for low-permeability sedimentary rocks using a conservative tracer, iodide (Cavé et al., 2009a, 2009b), and a sorbing tracer, cesium (Cavé et al., 2010; Loomer et al., 2013a), in synthetic Na-Ca-Cl porewater with an ionic strength of 8.3 mol/kgw. Reactive transport modelling, coupling diffusion and ion-exchange, was used to fit experimental data and quantify Cs-Na selectivity coefficients and the cation exchange capacity of intact low-permeability rock samples (Cavé et al., 2010; Loomer et al., 2013a, 2013b).

The radiography technique has been further developed and used to measure diffusion properties for Opalinus Clay samples from the DR-A experiment (see Section 4.4.2) at the Mont Terri URL in Switzerland (http://www.mont-terri.ch), with both iodide and cesium tracers. The diffusion coefficients for Cs estimated using X-ray radiography fall within the range of published values measured in both laboratory and in-situ field-scale diffusion experiments. The measured Cs-Na exchange selectivity coefficients are consistent with the range of published values (Loomer et al., 2013a, 2013b).

To assess the influence of stress relief on the estimated effective diffusion coefficients of rock core samples, through-diffusion measurements were conducted at the University of New Brunswick under re-applied lithostatic stress (12-17 MPa). Experiments were conducted with cores from Queenston and Georgian Bay shales and Cobourg Formation limestone obtained from 472-681 m below ground surface in the Michigan Basin. The diffusion coefficients determined under re-applied confining pressure are 10 to 40% lower than the diffusion coefficients determined at ambient laboratory pressure (Loomer et al., 2013a).

A gamma radiography technique using an Am-241 source was tested for measuring partial gas/brine saturation of sandstone, with the partial gas saturation created by N_2 gas using a pressure differential method. The tests indicate that the degree of partial saturation of the sandstone can be measured using γ-ray radiography. Porewater diffusion coefficients (D_p) of fully saturated and partially saturated sandstone samples were measured by γ-ray radiography. A trend of decreasing diffusion coefficient values was determined as the fraction of gas partial saturation increases. The γ-ray radiography technique was also used to study the diffusive properties of crystalline rocks. Diffusion coefficients measured by the γ-ray radiography method were compared with those measured by the through-diffusion method. The development of the γ-ray radiography technique will continue in 2014.

4.1.6 Assessment of Excavation Damaged Zone (EDZ)

In the APM program, the strategy for assessing the role of the EDZ in brittle rocks in the DGR concept is to: 1) gain an understanding of the role of the EDZ in the possible creation of discrete pathways for mass transport along the excavated and backfilled openings in sedimentary rock; 2) minimize the extent of damage to the host and surrounding rock mass through appropriate excavation methods; 3) minimize the dimensions of the EDZ by optimizing geometry of

excavated openings – based on knowledge of the stress state and influence of cut-off excavation on EDZ re-distribution; and 4) evaluate and develop sealing methods.

In 2013, Phase 1 of EDZ research was completed, which focused mainly on: 1) investigating existing excavations in limestone; 2) strength testing data on limestone; and 3) using continuum models to evaluate the dimensions of EDZs. The research included the development of a new geomechanics classification system for carbonate, siliciclastic and argillaceous rocks (Perras, 2014) in an effort to understand and anticipate rock mass behaviour that may be encountered at both the repository level and in the access shafts in sedimentary environments.

The excavation of any underground opening forms a zone of disturbed rock around it. Within this excavated disturbed zone (EdZ), there exists one or more zones with different degrees of rock damage along the wall of the excavation, classified as the excavation damaged zone (EDZ) and the highly damaged zone (HDZ) (Fracture Systems Ltd., 2011). These zones are identified in Figure 4.5 and are collectively referred to as the excavation damaged zones (EDZs). Damage initiation and fracture propagation will occur such that the crack intensity decreases with increasing distance from the excavated wall.

Depending on the constitutive model employed – the process of stress shedding (redistribution) and localization – the excavation damaged zones can evolve differently. Selection of the correct constitutive criteria is an important step in the design process. For brittle rock masses, the degree of jointing is minimal, with geological strength index (GSI) exceeding 75 (good to very good rock), and the behaviour is extensile-fracture dominated. The extensile fractures develop under compressive loading near the boundary of an excavation. Diederichs (2007) developed a simplified constitutive model approach, using the Damage Initiation and Spalling Limit (DISL) to represent the boundary sensitivity of brittle fracture. Based on model results, the yield elements, volumetric strain and principal stress concentration were found to be the best indicators for determining the dimensions of different EDZs.

A detailed numerical study of brittle behaviour was conducted in 2012 and the results determined that the following definitions of the EDZs can be used to delineate the zone dimensions for continuum models (Perras et al., 2012).

- *The HDZ – EDZ_i transition was taken as near zero and constant minimum principal stress and either maximum or rapidly increasing extensile or shear strain.*
- *The EDZ_i – EDZ_o transition was taken as the start of extensile volumetric strain.*
- *The EDZ_o – EdZ transition* was taken as the start of plastic yielding.

To develop predictive equations for the geometry and dimensions of these damaged zones, the crack initiation stress and unconfined compressive strength (UCS) data from shale (Queenston Fm.), limestone (Cobourg Fm.) and granite (for comparison) materials were used as input parameters to simulate a circular excavation. With a large number of model results, statistical probability of EDZs dimensions was generated, demonstrating the degree of confidence in EDZ dimensions. The model results were also used to develop empirical relationships useful for preliminary estimation of the extent of excavation damage around a circular excavation in brittle rock (Figure 4.6).

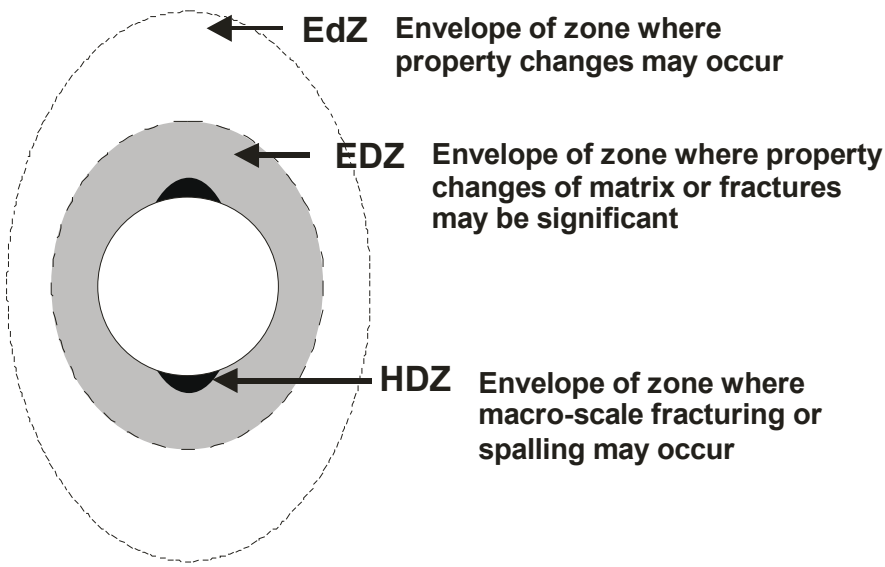


Figure 4.5: The Excavation Damaged Zones (EDZs), Which Include the Excavation Damaged Zone (EDZ), the Highly Damaged Zone (HDZ) and the Excavation Disturbed Zone (EdZ; Fracture Systems Ltd., 2011); The EDZ Can be Further Subdivided into Inner (EDZ_i) and Outer (EDZ_o) Zones (not shown)

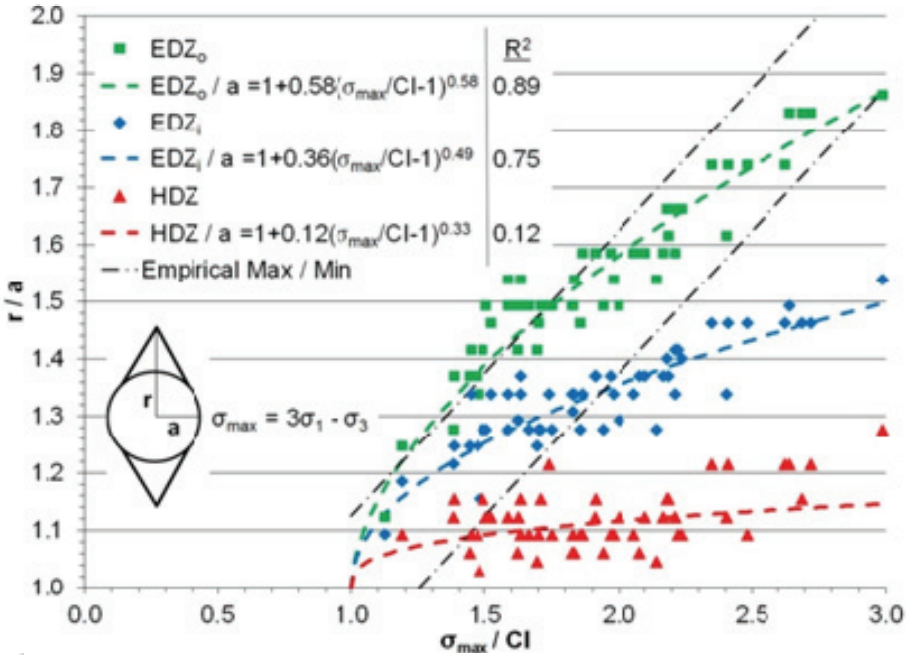


Figure 4.6: EDZ Prediction Equations for a Circular Excavation in Cobourg Limestone (Perras and Diederichs, 2014)

Research into EDZ detection using Ground Penetrating Radar and Electrical Resistivity Tomography were conducted in collaboration with the Norwegian Geotechnical Institute at the Äspö HRL. The geophysical measurements were verified using fracture information logged in 7 shallow boreholes. Data processing results show promising detection possibilities. There appears a relatively good agreement between the two methods (Walton et al., *in press*).

Underground applications of LiDAR have been on-going at Queen's University since 2008. Most recent studies have been focused on deformation monitoring and methodologies for processing LiDAR data to increase accuracy (Delaloye et al., 2014). Collaboration on the use of highly accurate Laser Profile with Amberg Engineering AG has also been initiated. This technology was recently applied to liner deformation monitoring at the Niagara Tunnel Project in Ontario.

For EDZ cut-off design it is important to understand post-yield and time-dependent deformation processes, and how these can be best captured numerically. To this end, a numerical study has been initiated using dilation modelling to assess, in part, the phenomena of mass creep. The above processes are particularly important in the context of understanding the cut-off influence on rock mass behaviour if cut-off structures are to be excavated, for example, many years after the initial repository excavation. A cut-off is intended to mitigate radionuclide migration and, as such, must bisect the HDZ and key into the EDZ to have the greatest effect. The depth of cut-off can be determined using the HDZ and EDZ definitions described above. However, the excavation of the cut-off itself will induce fracture propagation and plastic yielding. Wedge, edged-box and slot cut-off geometries were modelled to investigate the impact on these shapes on the development of plastic yielding around the structures.

Other numerical indicators, such as proximity to lithological contacts, slot thickness and spacings between consecutive cut-offs, were also examined. The preliminary results show the slot cut-off appears to isolate plastic yielding at the slot tip from the yielding around the excavation. Figure 4.7 shows a 0.25 m wide cut-off is adequate to achieve a cut-off effect. An optimum spacing is between 5 and 6 m if multiple cut-offs are employed in a seal system. Further study is necessary to incorporate the anisotropic nature of the rock and the existing damaged fractures induced in the rock during initial excavation, as the cut-off will be constructed some years after the completion of the repository shafts or tunnels.

Research will continue on EDZ-related issues in sedimentary rocks in 2014 and will focus on the investigation of post-yield dilatancy in HDZ, time-dependent behaviour, pore pressure interaction within the EDZ, EDZ verification and management using excavation cut-offs.

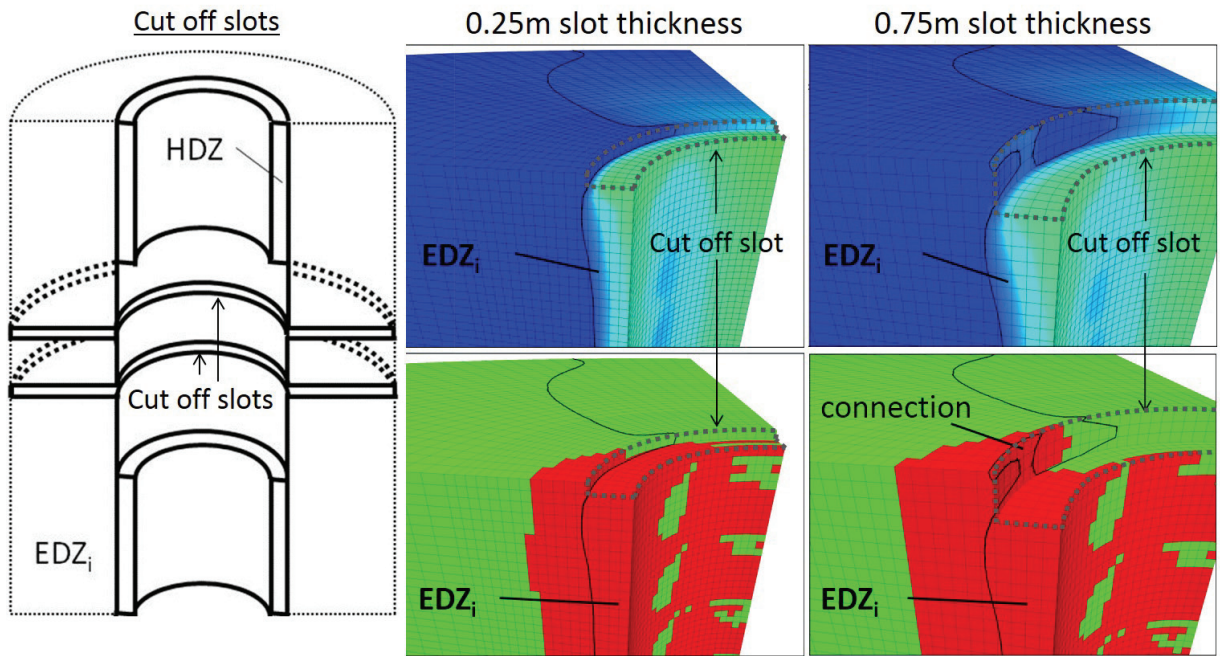


Figure 4.7: Cut-off Slot Thickness (0.25m and 0.75 m) Analysis Using Volumetric Strain (contraction to extension transition – black line) as a Cut-off Criterion; the Lower Middle Figure Shows Both HDZ and EDZi Being Cut-off by a 0.25 m Wide Slot, Whereas Links Remain with a Wider Slot (Perras, 2014)

4.1.7 Anisotropy and Scaling of Coupled Hydro-mechanical Properties of Rock

The Phase 1 experimental research program examining the effects of anisotropy and scaling on measured hydro-mechanical properties has been completed at McGill University. The experiments involved axial and radial transient hydraulic pulse testing on Cobourg limestone retrieved primarily from the St. Mary's Cement quarry in Bowmanville. The former was carried out using a GDS high pressure triaxial cell (Figure 4.8) because of its ability to reconstitute the sample state of stress consistent with that at the sample recovery depth, and to investigate the evolution of permeability hysteresis under such a stress state. Specimen sizes up to 100 mm in diameter were used, with the intention to adequately capture the role of internal fabric (i.e., anisotropy) on the representative properties of limestone as they relate to physical, mechanical and fluid transport behaviour. Sample testing revealed axial permeabilities (perpendicular to bedding partings) ranging from 2.7 x 10^{-22} to 0.2 x 10^{-22} m^2 under a low confinement condition of 5 MPa (Selvadurai et al., 2011).

Eighty-one hydraulic pulse tests were performed on two samples to establish the process of permeability evolution in rocks with a dominant internal fabric under the application of isotropic states of stress. The observed behaviour was contrary to typical observations in uniform rock material, for which an irreversible decrease in permeability due to effects such as pore closure and collapse mechanisms is anticipated. Further experimental investigations on this observed behaviour will continue in the next phase of research. For the radial transient hydraulic pulse testing, only a limited number of 106 mm diameter samples were tested. Figure 4.9 shows a

cross-section of the testing arrangement. The experiments gave permeabilities in the range of 1.0 x 10^{-22} to 1.7x 10^{-19} m^2 for radial flow, which are oriented along bedding partings under zero axial stress (Selvadurai and Jenner, 2012). These are within the range of permeability measurements documented in the literature. Despite the heterogeneous nature of the Cobourg Limestone, the rock permeability appears to be directional independent.

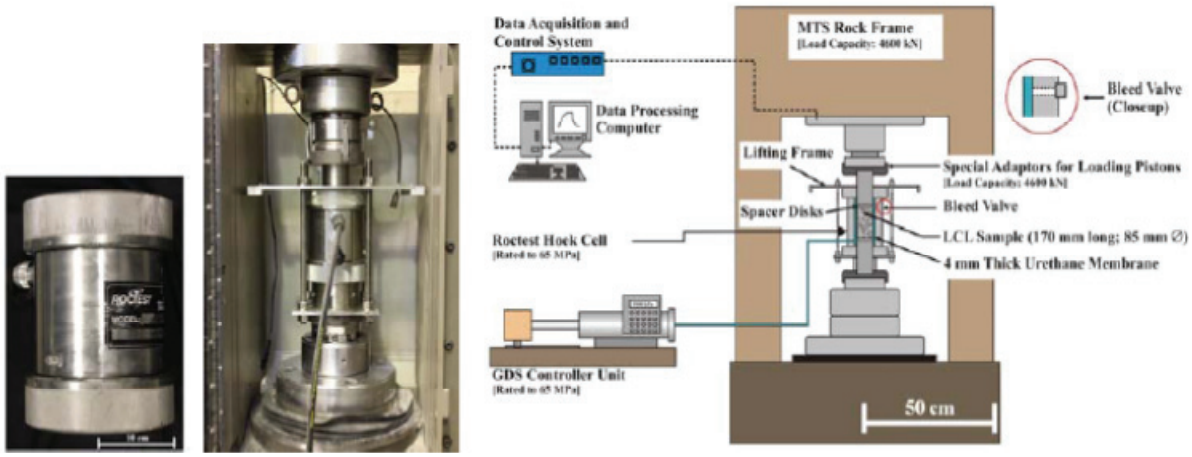


Figure 4.8: GDS Triaxial Cell and Ancillary Equipment for Hydraulic Pulse Tests

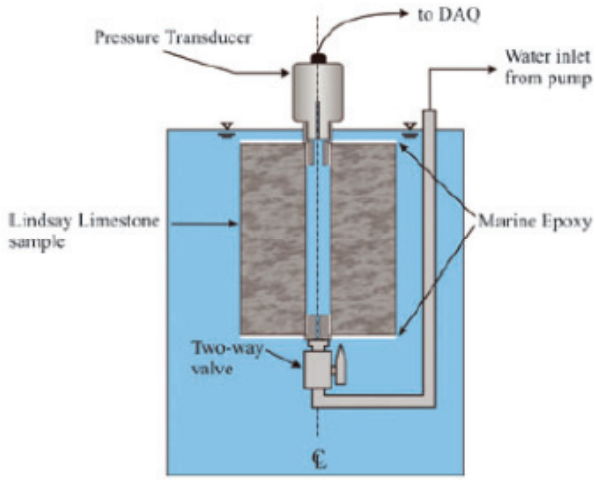


Figure 4.9: Radial Transient Hydraulic Pulse Test Set-up

4.2 SITE CHARACTERIZATION – REGIONAL SCALE

4.2.1 Paleoseismicity

In 2012, NWMO joined an on-going Paleoseismicity study within the Ottawa-Bonnechere Graben being conducted by the Geological Survey of Canada (GSC) (Figure 4.10).
This work program relates to several important issues with respect to APM DGR siting, site characterization and safety case development, including: 1) extension of the existing seismic activity record beyond that currently available (≈160 years); 2) improving understanding of earthquake frequency and magnitude following ice-sheet retreat; 3) providing improved seismic data to substantiate assessment and influence of earthquakes in a DGR safety case (i.e., Seismic Hazard Assessment); and 4) providing additional data to assess geosphere stability as it relates to engineered barrier system performance and far-field barrier integrity. A draft report was delivered in December 2013 with a final report and associated paper to be delivered in the first quarter of 2014. In addition, further paleoseismicity work with the GSC will be continued in the Rouyn-Noranda region between 2014 and 2017.

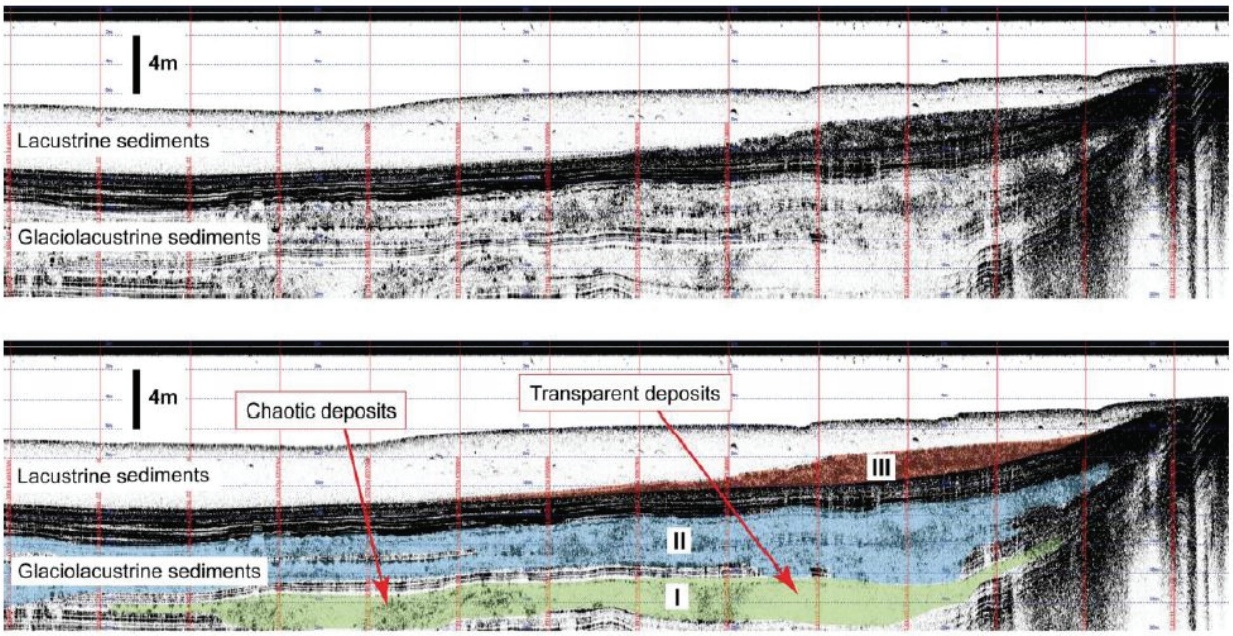


Figure 4.10: Uninterpreted (upper) and Interpreted (lower) Versions of the Same (sub-bottom acoustic profile) SAP Returns, Showing Three Sets of Disturbed Deposits within the Sub-bottom of Lake Arnoux, Near Noranda, Quebec; the Deposits Labeled I and II Occur within Glaciolacustrine Deposits and Those of Layer III at the Interface between the Glaciolacustrine and Overlying Lacustrine Deposits. Note the Chaotic and Transparent Character of the Returns within Disturbed Deposits. The Mechanism that Initiated the Disturbed Deposits has not Been Investigated, but Paleoearthquakes are a Potential Trigger

4.2.2 Seismic Monitoring of the Canadian Shield

NWMO continues to gain knowledge on the seismic characteristics of low seismicity regions of the Canadian Shield in collaboration with the Canadian Hazard Information Service (CHIS) of the Geological Survey of Canada (GSC). The purpose of NWMO participation is to monitor the low levels of background seismicity in the stable cratonic region of the Canadian Shield. The CHIS monitoring network consists of 18 seismograph stations situated from Pinawa, Manitoba, in the west, to Chalk River, Ontario, in the east. All stations record real-time, continuous, digital data, which are transmitted by satellite to the GSC data laboratory in Ottawa. An annual report prepared by the CHIS documenting seismic activity in 2013 will be available in 2014.

4.3 NUMERICAL MODELLING PROGRAMS

4.3.1 Reactive Transport Modelling

Reactive transport modelling is a useful approach for assessing long-term hydro-geochemical stability within geological formations. For example, reactive transport modelling can be used to assess and gain insight on: 1) the degree to which dissolved oxygen in meteoric or glacial recharge may be consumed in the sub-surface; 2) how geochemical reactions (e.g., dissolution-precipitation, oxidation-reduction, aqueous complexation and ion exchange reactions) may alter geochemical signatures or physical hydrogeologic conditions along migration pathways; and 3) how diffusive transport of reactive solutes may evolve in the porewaters of low-permeability geological formations.

MIN3P is a multi-component reactive transport code that has been previously used to evaluate redox stability within crystalline groundwater systems typical of the Canadian Shield (Spiessl et al., 2009). Research has been conducted in collaboration with the University of British Columbia and the University of New Brunswick to develop an enhanced version of MIN3P (named MIN3P-THMc) that has been used to simulate groundwater flow and reactive mass transport in a sedimentary basin subjected to a single glaciation/deglaciation cycle (Bea et al., 2011). The code enhancements included: 1) calculation of ion activity corrections in high ionic strength (up to 20 mol/L) solutions using the Harvie-Möller-Weare model, which is based on Pitzer equations; 2) calculation of fluid density for high ionic strength solutions; 3) one-dimensional hydromechanical coupling to improve simulation of transient ice-sheet loading; and 4) coupled heat, fluid and solute transport.

4.3.2 Deep Groundwater Systems Evolution

NWMO continues to develop numerical methods to assess and quantify the robustness of site characterization data and predict groundwater flow and transport over geologic timescales, as relevant to the safety case. Numerical methods are used to assemble and test descriptive geosphere conceptual models, which are usually developed from the integration of multidisciplinary data sets that can include site-specific characterization data. In addition, numerical models are used to refine the understanding of groundwater system evolution in both crystalline Canadian Shield and sedimentary basin environments.

In order to investigate the evolution of groundwater systems and assess the long-term performance of a DGR, NWMO is actively collaborating with researchers at the University of Waterloo. The objective is to refine numerical geosciences tools and methods to characterize groundwater systems. FRAC3DVS-OPG, the groundwater model chosen by the NWMO, is being applied to investigate the factors influencing groundwater system evolution in regional and sub-regional settings, and to test descriptive conceptual geosphere models. FRAC3DVS-OPG is a code that provides a solution of three-dimensional, density-dependent groundwater flow and solute transport in porous, discretely-fractured media.

In 2013, sub-regional scale groundwater modelling in sedimentary rock was undertaken in support of the APM pre-project review. A suite of temperate and paleohydrogeologic sensitivity cases were simulated in order to illustrate the role the geosphere plays in maintaining groundwater system stability at repository depths. The suite of sensitivity cases investigated the role of salinity and hydromechanical coupling during paleohydrogeologic simulations. MLEs, depth of penetration of recharge during paleoclimate scenarios, and Peclet numbers were used as performance measures to illustrate the processes governing mass transport. For an assumed reference case, the shallow groundwater system is advective, and at greater depths, the low permeability of the rock mass and increased TDS concentrations result in decreased mass transport rates.

Paleohydrogeologic simulations were used to illustrate the long-term evolution and stability of the geosphere and groundwater systems to external perturbations. For the paleohydrogeologic sensitivity cases performed, the glacial perturbations did not materially change mass transport rates at repository depth.

In addition to the support for the APM pre-project review, groundwater modelling was undertaken as a part of the Greenland Analogue Project (GAP) in 2013 (Yin et al., 2013) to illustrate the influence of alternate conceptual models, parameters and scenario uncertainty on the subsurface groundwater system and various performance measures.

4.3.3 Discrete Fracture Network

Fracture network modelling involves using 3-dimensional, geostatistical tools to create realistic, structurally possible models of fracture zone networks that honor field observation. The ability to realise the fracture network uncertainty in terms of geometry, properties and interconnectedness within numerical flow and transport models is necessary to illustrate scenarios for groundwater system evolution.

As demonstrated by Sykes et al. (2004) and Normani et al. (2007), fracture network models can be incorporated into groundwater flow models. These models, in turn, can be used to explore the long-term stability and evolution of deep groundwater systems at crystalline rock sites in response to perturbations, such as glacial events. In crystalline rocks, the presence and distribution of fracture zones in the geosphere strongly influences groundwater system dynamics and evolution. The predominant pathway for solute migration is through the interconnected network of permeable fractures. Therefore, it is important to have structurally possible, geostatistically representative fracture networks that are directly derived from field-data collected during surface and sub-surface investigations.

Previously, fracture network models have been created using legacy software known as FXSIM3D for the Whiteshell Research Area (Srivastava, 2002a) and for the Sub-regional Shield

Flow System case study (Srivastava, 2002b). This fracture network model was subsequently used for the Used Fuel Repository Conceptual Design and Postclosure Safety Assessment in Crystalline Rock (NWMO, 2012a). A third fracture network model was created to verify and validate the fracture modelling procedure based on quarry field data from Lägerdorf, Germany (Srivastava and Frykman, 2006).

Together with MIRARCO and the Centre for Excellence in Mining Innovation (CEMI), an accessible and extensible version of the code, referred to as MoFrac and based on the original FXSIM3D code, was created. The development of the MoFrac code enables the generation of geostatistically and structurally representative fracture network models for potential use in future site characterization activities and for geosphere simulations to support the safety case and repository design for potential crystalline rock sites.

A key part of the NWMO's postclosure studies is the predictability and long-term performance of the geosphere surrounding the used fuel repository. This includes developing an understanding of the potential effects of earthquakes on the repository and the influence of future glacial cycles on deep groundwater systems. The NWMO successfully concluded its involvement in the Greenland Analogue Project (GAP) in 2013 and continues to expand investigations of seismicity and paleoseismicity.

4.3.4 Glacial Systems Model

The ability to predict surface boundary conditions during glaciation is an essential element when assessing the potential impact of glaciation on a DGR. These boundary conditions can include permafrost extent and depth, ice-sheet properties (extent, thickness and kinematics) and ice-sheet hydrology. For NWMO's glaciation case studies, these boundary conditions have been defined based on the University of Toronto's Glacial Systems Model (GSM) predictions (Peltier, 2002, 2006). The GSM is a state-of-the-art model of continental scale ice-sheet evolution which allows the reconciliation and integration of a large body of observational constraints governing ice advances and retreats over the North American continent during the Late Quaternary Period of Earth history.

There are several aspects of the GSM that are being enhanced to improve the fidelity of the predictions of glaciation boundary conditions and, consequently, increase the support for the DGR safety case. In the previous model, which is based upon the "shallow ice approximation", longitudinal stresses are neglected. The objectives of the on-going research in support of the University of Toronto work program are to maintain and improve the GSM. These objectives will be achieved by improving the representation of the flow of ice over the landscape in the GSM by implementation of higher degree physics. The improvements to the physics and numerical methods implemented in the GSM allow are more robust representation of the glacier, as opposed to the previously implemented shallow ice approximation.

4.4 INTERNATIONAL ACTIVITIES

4.4.1 Greenland Analogue Project (GAP)

NWMO, in collaboration with SKB and POSIVA, completed the final full field season of the Greenland Analogue Project (GAP) in 2012, and focus switched in 2013 to preparing the final

reports. The objective of this four-year project (2009-2012) was to advance the understanding of processes associated with glaciation and their impact on the long-term performance of a DGR. The improved knowledge and how it allows us to evaluate the impact of an ice sheet on groundwater chemistry at repository depth (using the Greenland ice sheet as an analogue to future glaciations in North America) will be documented in the 2 volume set of Greenland Analogue Project final reports.

Following an introductory field campaign in 2008 near Kangerlussuaq, Greenland, the GAP field program began in 2009 and included the successful initiation of ice sheet and geosphere/geochemistry studies. Through an extensive field and modelling program, the GAP aimed to assess glacial hydrology, groundwater flow and groundwater composition (particularly redox conditions) at the base of a continental-scale ice sheet (see Figure 4.11).

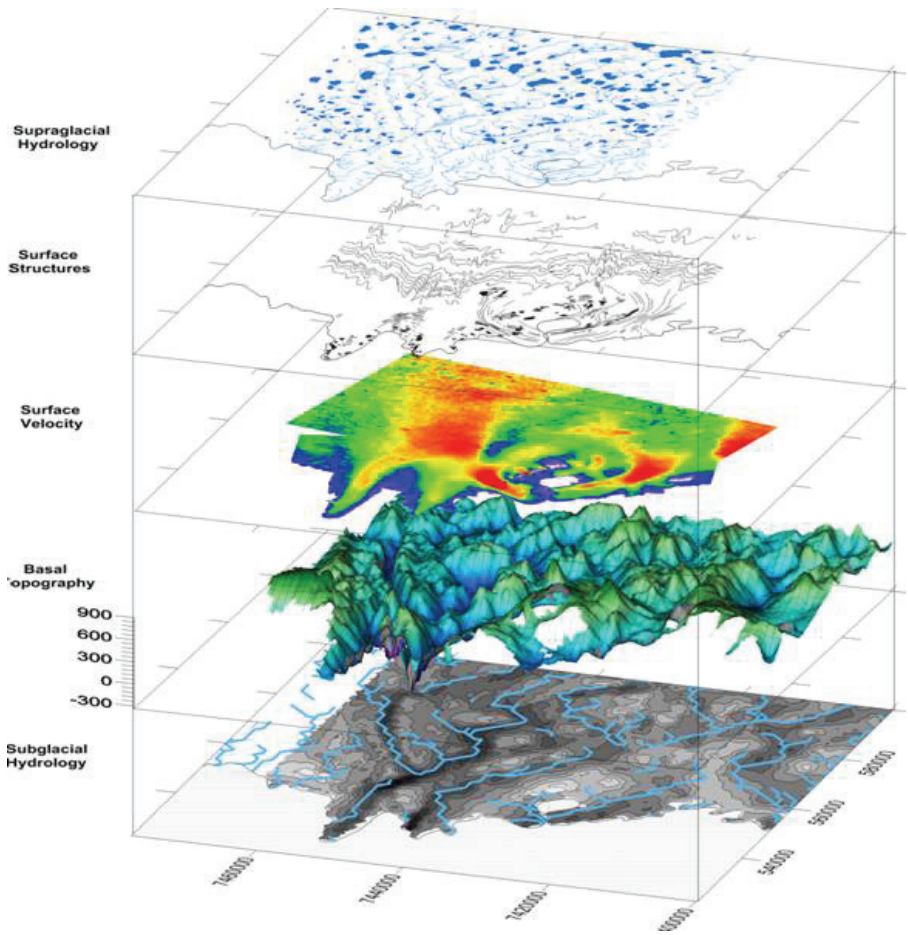


Figure 4.11: Conceptualization of Integrated Datasets Relating to the Glacial Hydrology of the Greenland Ice Sheet, Near Kangerlussuaq, Greenland

Research conducted on the surface of the ice sheet has included the installation of GPS stations, ground-based radar and remote sensing of the study area, tracer tests conducted near the ice margin to look at water flow from the surface to the base of the ice sheet, and boreholes drilled through the ice to the ice bed. A deep, inclined borehole (DHGAP04, ~687 m borehole

length) was successfully drilled under the margin of the ice sheet. The borehole was instrumented with a multi-level packer system below the permafrost to allow for the measurement of temperature, pressure, electrical conductivity, transmissivity of open fractures and hydraulic head. Both core and porewater samples were collected from the deep borehole, with an additional set of water samples collected in the Fall of 2013.

In 2013, the focus of GAP switched from field activities to final reporting. The first volume of the GAP final reports (GAP Data Report) was drafted in 2013, and plans for the second volume report (GAP Final Synthesis Report) were completed. In 2014, focus will be on completing the GAP Final Synthesis Report. The two reports will be published concurrently, with publication planned for 2015.

4.4.2 Mont Terri

Full-scale Emplacement (FE)

In 2013, NWMO was a project partner in several experiments at the Mont Terri URL, Switzerland. One of these experiments was the FE or Full-scale Emplacement experiment. The FE demonstration experiment evolved from an earlier engineered barrier experiment and was designed to demonstrate the feasibility of emplacing spent fuel waste containers for deep geological disposal, as well as to investigate the thermo-hydro-mechanical (THM) coupled effects on host rock and the engineering barrier system (EBS). The general arrangement of the experiment is shown in Figure 4.12. It is an experiment that is carried out at a 1:1 scale. The behaviours of backfill material and rock under the influence of temperature are monitored as the containers are heated to simulate the heat generated by radioactive waste. Measurements will be made over the next several decades. Currently, excavation of the experiment is complete and installation of near-field (EDZ) instruments is in progress. Upon completion, there will be several hundred sensors installed to monitor temperature, porewater pressure, water content and suction, deformations and stresses throughout the duration of the experiment (Figure 4.13). In 2014, the instrumentation, backfilling and seal/plug construction will be completed and heating will begin to simulate post-closure conditions.

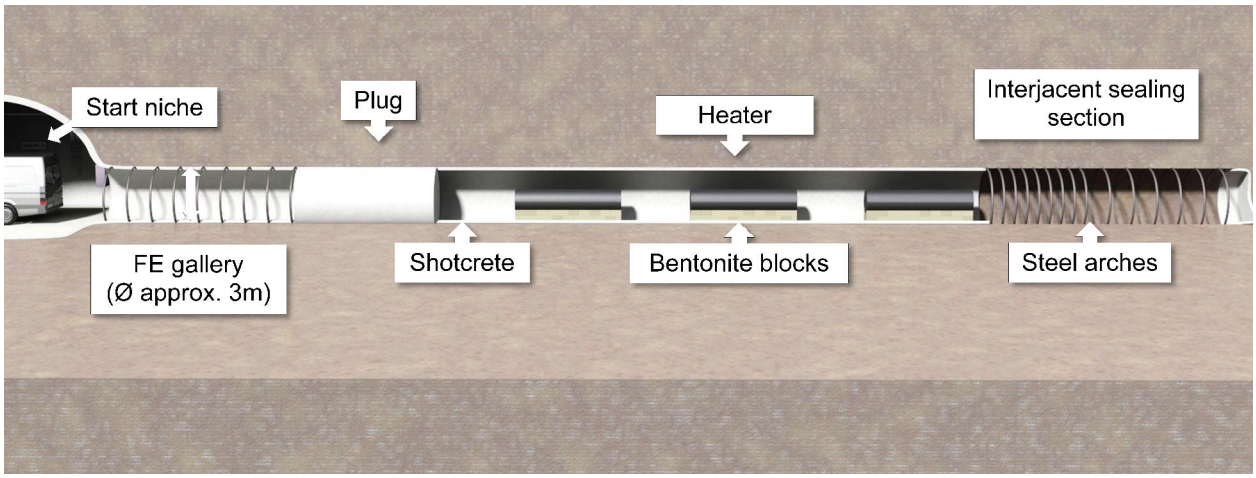


Figure 4.12: Visualization of Final Arrangement of FE Experiment at Mont Terri URL (Vogt, 2013)

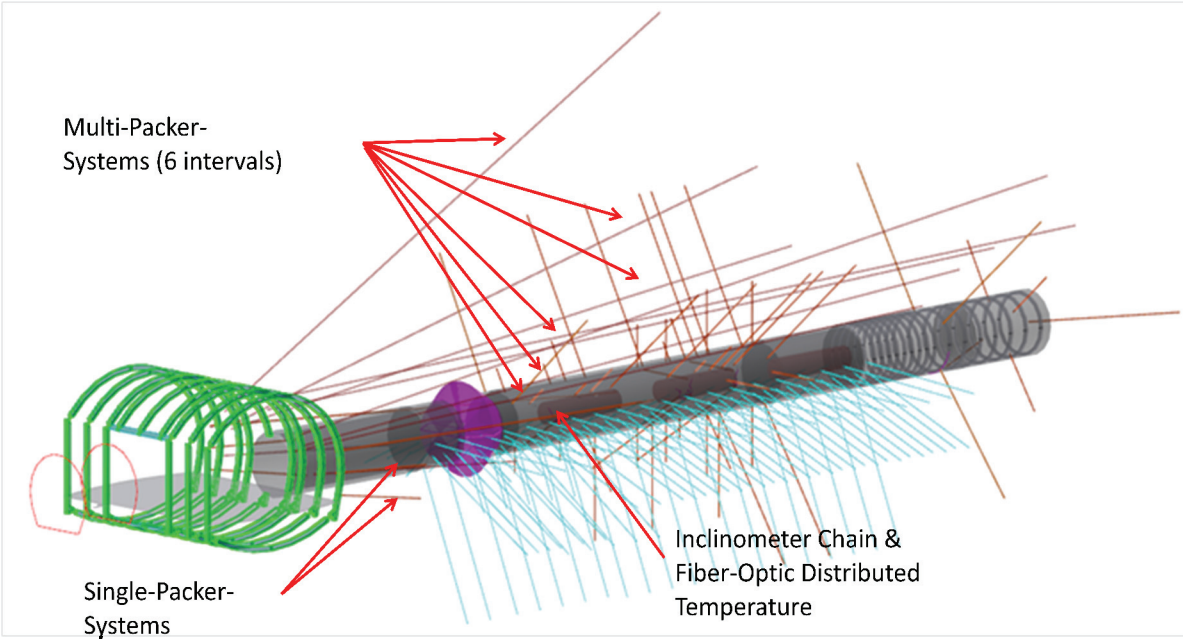
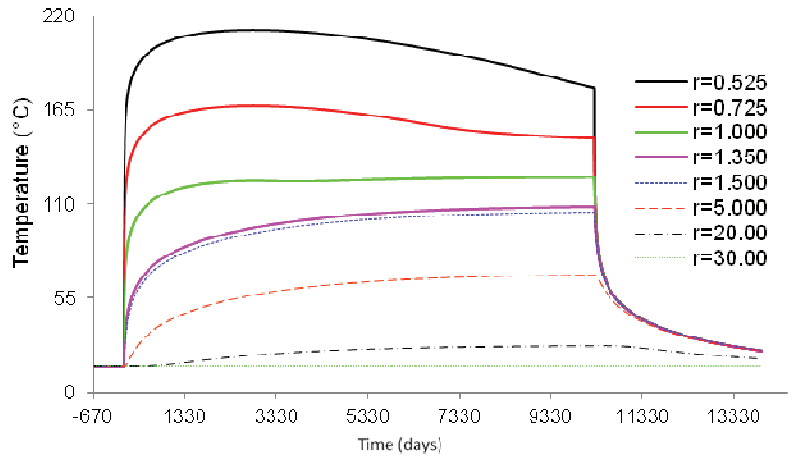


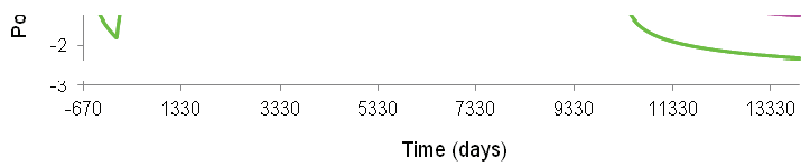
Figure 4.13: Layout of Instrumentation of the Test Adit of FE Experiment (Vogt, 2013)

To improve the current state of knowledge of the THM coupled response of the host rock and the EBS, a one-dimensional finite element model was created as part of a prediction exercise to simulate the coupled responses of the Opalinus Clay host rock and the EBS. The THM coupled responses in the bentonite backfill, shotcrete and host rock were successfully modelled at different stages up to 40 years after repository closure using the finite element code, CODE_BRIGHT (Olivella et al., 1996). Figure 4.14 shows results of the simulation of temperature and pore-pressure response in bentonite backfill and host rock at various locations from the tunnel axis (Guo, 2014 *in preparation*).

In 2014, analyses will be performed by NWMO as part of the THM study in order to simulate the construction sequence of the FE Experiment niche and to compare results to the available monitoring data. Displacement and pore pressure data ahead of and behind the face of the FE niche excavation will be obtained in order to study post-yield dilatancy, time dependency, pore-pressure behaviour and EDZ development.



(a)



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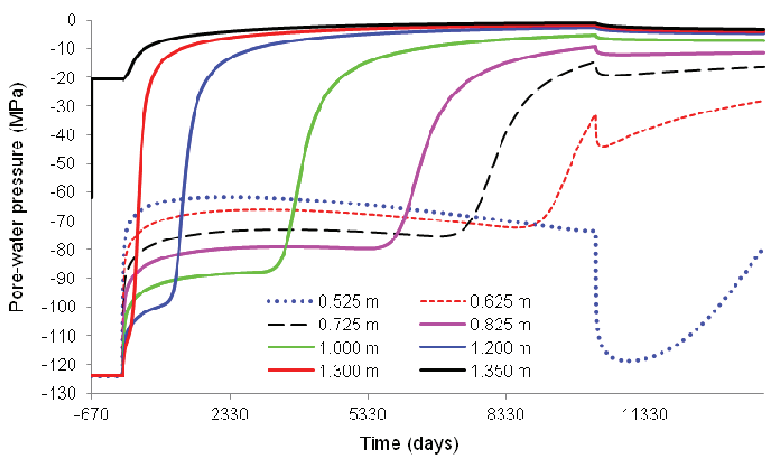


(c)

Figure 4.14: Temperature (a) and Porewater Pressure (b) in Opalinus Clay and (c) in Bentonite versus Time at Different Locations from the Tunnel Axis

Deep Borehole (DB and DB-A)

As a part of the Mont Terri Project, the goal of the DB is to develop and validate a methodology for assessing the contaminant transport properties of a thick argillaceous formation using the

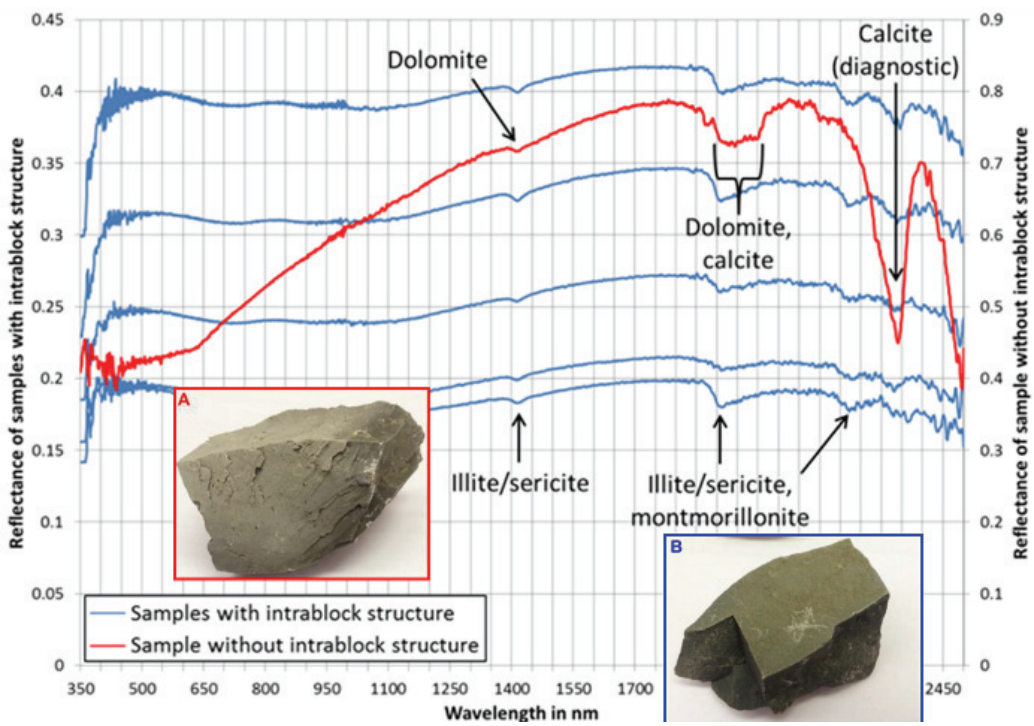


Figure 4.19: XRD Test Results of Limestone with and without Intrablock Structures

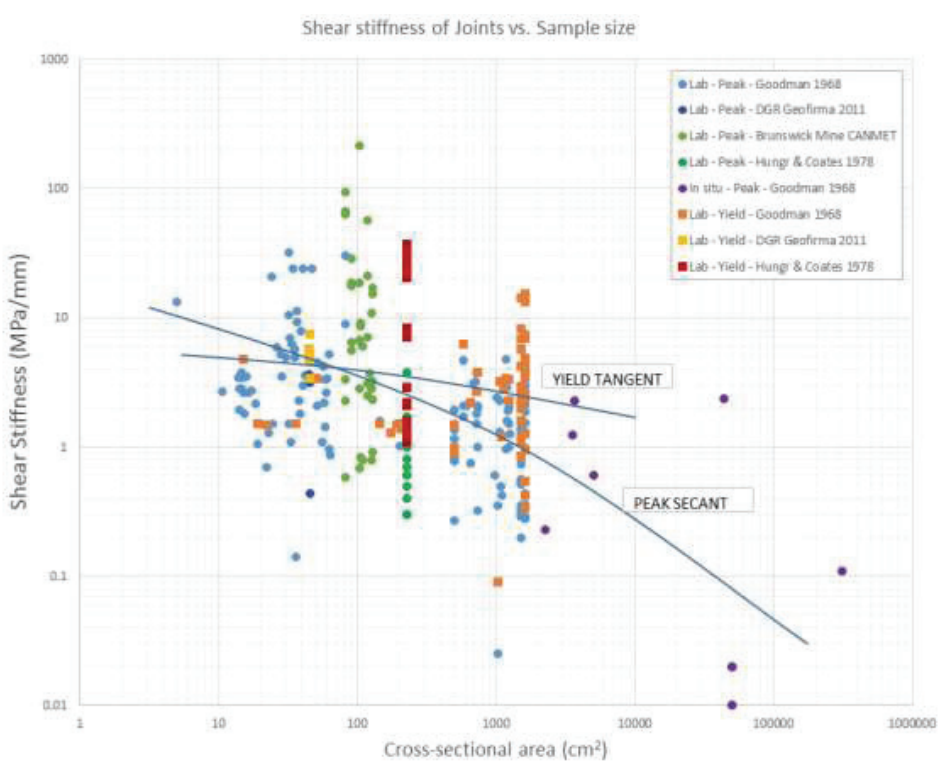


Figure 4.20: Scale Dependency of Shear Stiffness Coefficients

5. REPOSITORY SAFETY

The objective of the repository safety program is to evaluate and improve the operational and long-term safety of any candidate deep geological repository. In the near-term, before a candidate site has been identified, this objective is addressed through case studies and through improving the understanding of important features and processes. Activities conducted in 2013 to further this objective are described in the following sections.

Garisto et al. (2009) provides a technical summary of information on the safety of a repository for used nuclear fuel. The report summarizes key aspects of the repository concept and explains why the repository concept is expected to be safe (see Table 5.1). The report is non-site specific and considers both Canadian Shield and sedimentary rock formations. Several design concepts are considered.

Table 5.1: Typical Physical Attributes Relevant to Long-term Safety

Repository depth provides isolation from human activities
Site low in natural resources
Durable waste form
Robust container
Clay seals
Low-permeability host rock
Spatial extent and durability of host rock formation
Stable chemical and hydrological environment

5.1 MODEL AND DATA DEVELOPMENT

5.1.1 Wasteform Modelling

The first barrier to the release of radionuclides is the used fuel matrix. Even if a container fails, most radionuclides remain trapped within the UO_2 grains, and are only released as the fuel itself dissolves. The rate of fuel dissolution is, therefore, an important parameter for assessing long-term safety.

UO_2 dissolves extremely slowly under reducing conditions similar to those that would be expected in a Canadian deep geological repository. However, in a failed container that has filled with groundwater, used fuel dissolution may be driven by oxidants, particularly hydrogen peroxide (H_2O_2) generated by the radiolysis of water. The mechanistic understanding of the radiolytic corrosion of UO_2 is important for long-term predictions of used fuel stability.

Within the last several years, dissolved hydrogen gas (H_2) has been confirmed as a key factor in the corrosion process. Hydrogen is generated from radiolysis, but much larger amounts are generated as a result of corrosion of the steel vessel of the container.

The 2013 program on UO_2 dissolution continued at Western University and included:

- development of a model to predict the influence of steel corrosion products (Fe^{2+} and H_2) on the fuel corrosion rate;
- investigation of the influence of trivalent dopants on the properties of UO_2 (Razdan and Shoesmith, 2014); and
- determination of the kinetics of H_2O_2 reduction and decomposition on a SIMFUEL (UO_2) surface.

This work will be submitted for journal publication in 2014.

A combination of electrochemical and open circuit corrosion measurements on UO_2 electrodes and surface analytical techniques were used in the investigations. The tests were conducted with SIMFUELs, or Gd- and Dy-doped UO_2. SIMFUEL (simulated high-burnup UO_2-based fuel) is made by doping unirradiated natural UO_2 pellets with non-radioactive elements to replicate the chemical composition of used fuel, including the formation of so-called ε-particles – alloys of the fission products Mo, Ru, Tc, Pd and Rh. The results of the research undertaken at the University of Western Ontario are summarized in Sections 5.1.1.1 to 5.1.1.3.

Work was initiated in 2013 to rigorously determine and document the margin to criticality for a set of bounding operational and postclosure scenarios and configurations. The work is discussed in Section 5.1.1.4. Also, a report summarizing discharge burnups and maximum power ratings was published, updated to reflect 2006-2012 data, and the results are presented in Section 5.1.1.5.

5.1.1.1 Model to Predict the Influence of Redox Conditions on Fuel Corrosion

The model of fuel corrosion developed in earlier work (Wu et al., 2012) was improved in 2013. The aim of this model is to predict the corrosion rate of fuel inside a failed used fuel container (fuel corrosion can only occur if water contacts the fuel). In particular, the model determines the effects of steel corrosion products (Fe^{2+} and H_2) – which influence redox conditions inside a failed container – on the fuel dissolution rate (Wu et al., 2012). The key oxidant promoting fuel dissolution in a failed container is H_2O_2 generated by the alpha-radiolysis of water (Eriksen et al., 2012).

The model improvements are listed below.

- A complete set of alpha-radiolysis products (e.g., H_2O_2, $H^{\bullet}$, $OH^{\bullet}$) and reactions was included; previously, H_2O_2 was considered the only significant oxidant.
- The influence of fuel burnup was included through the alpha-dose rate and surface reactivity of the fuel.
- The oxidative dissolution of UO_2 was changed from a general surface reaction, to a model that accounted for anodic dissolution supported by H_2O_2 reduction on both the UO_2 and noble metal particle surfaces. In the previous model, a deliberately conservative rate constant was assumed for the general surface reaction. In this revised model, the rate constant for direct oxidative dissolution of UO_2 by H_2O_2 was decreased by 3 orders of

magnitude, consistent with new experimental data available in the literature. As well, the percentage coverage of the UO_2 surface by noble metal particles (approximately 1%) was taken into account.

- The influence of the reaction of H_2 and H_2O_2 catalyzed on noble metal particles was considered.

Radiolysis is assumed to occur uniformly within a thin layer of solution at the fuel surface. A diffusion layer represents the separation between the fuel surface and the undisturbed source of Fe^{2+} and H_2 (assumed to be formed by corrosion of the iron container). As with the original model, the improved model was not particularly sensitive to the diffusion layer thickness. For the results reported below, the alpha dose rate is $9x10^5$ Gy/a, which is the dose rate for CANDU fuel with a burnup of 220 MWh/kgU 1000 years after discharge.

Calculations using the new model indicate that if only H_2O_2 production is considered (as in the previous model), then the concentration of H_2O_2 in solution near the fuel surface is overestimated by about one third, leading to a higher fuel corrosion rate. The revised model shows there is consumption of H_2O_2 by reaction with reducing alpha-radiolysis species (e.g., $H^{\bullet}$). This result indicates that the assumption that only H_2O_2 is generated by alpha-radiolysis is an acceptable and slightly conservative approximation.

The Fenton reaction (i.e., the reaction between Fe^{2+} and H_2O_2) will also consume H_2O_2 and suppress fuel corrosion. In contrast to the previous model (Wu et al., 2012; Crowe et al. 2013), Figure 5.1 indicates that the influence of Fe^{2+} is significant. The fuel corrosion rate decreases by half as the Fe^2 concentration is increased from zero to 0.1 µmol/L (i.e., 10% of the solubility limit for $Fe(OH)_2$). Greater sensitivity to $[Fe^{2+}]$ is primarily due to the changes in the model for UO_2 corrosion (e.g., the revised rate constant for direct oxidative dissolution of UO_2 by H_2O_2 which was decreased by 3 orders of magnitude). Significant reduction in the overall fuel corrosion rate renders the rate much more sensitive to $[Fe^{2+}]$.

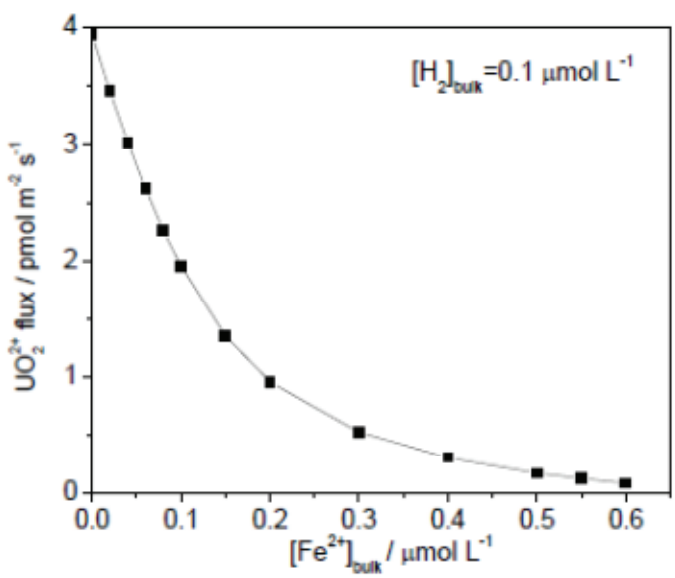


Figure 5.1 : Influence of Fe^{2+} Concentration on the UO_2 Corrosion Rate, Expressed in Terms of the Flux of UO_2^{2+} Leaving the Surface

One purpose for developing the model further is to examine the influence of H_2 on the fuel corrosion rate. Figure 5.2 shows that the calculated fuel corrosion rate depends on H_2 concentration. The fuel corrosion rate is significantly suppressed as the bulk hydrogen concentration increases. For $[H_2] > 0.51$ µmol/L, the fuel corrosion rate becomes zero, indicating that the rate of UO_2 oxidation/dissolution by H_2O_2 is balanced by the rate of its reduction by H_2. The H_2 concentration at which fuel corrosion is completely suppressed is called the critical H_2 concentration. The critical H_2 concentration is about one order of magnitude lower than that calculated with the previous model, primarily due to the new rate constants adopted for UO_2 corrosion.

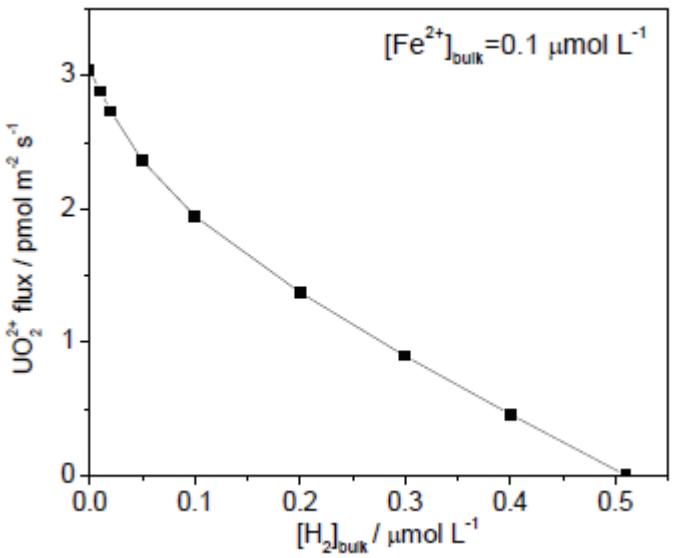


Figure 5.2: Effect of H_2 on the Concentration on the UO_2 Corrosion Rate, Expressed in Terms of the Flux of UO_2^{2+} Leaving the Surface

5.1.1.2 Influence of Trivalent Dopants

Used fuel is mainly UO_2, with the remainder being fission products and actinides produced during in-reactor irradiation. The key change most likely to influence the chemical reactivity of the UO_2 matrix is the trivalent rare earth (RE^{III}) doping of the matrix. The influence of RE dopants on the structure, composition and electrochemical reactivity of UO_2 was investigated in 2013 using surface analytical techniques and cyclic voltammetry (CV) (Razdan and Shoesmith, 2014). This was done by comparing the behaviour of undoped $UO_{2.002}$, a slightly doped 1.5 at% SIMFUEL, and two RE^{III} doped UO_2 specimens (6 wt% Gd-UO_2 and 12.9 wt% Dy-UO_2).

The reactivity of the specimens was found to decrease in the order $UO_{2.002}$ > SIMFUEL > Dy-UO_2 > Gd-UO_2, as shown in Figure 5.3, and indicating that the decrease is a consequence of RE^{III} doping. Note that at a potential of 0 V, the electrode would be expected to be oxidized to UO_{2+x} and the current to approximately reflect the rate of the reaction $UO_2 \rightarrow UO_{2+x}$; at 0.3 V, the current would be representative of the rate of the reaction $UO_{2+x} \rightarrow UO_3 \cdot yH_2O/UO_2^{2+}$.

Raman spectroscopy showed this difference could be attributed to formation of RE^{III}-oxygen vacancy clusters, the formation of which decreases the availability of the oxygen vacancies required to accommodate the injection of oxygen interstitials during anodic oxidation of UO_2.

The more heavily doped Dy-UO_2 would have been expected to be even less reactive than the Gd-UO_2, if anodic reactivity was controlled solely by the influence of the formation of RE^{III}-oxygen vacancy clusters. However, the electrochemical results in Figure 5.3 do not support this interpretation, suggesting that the UO_2 reactivity is also dependent on the nature of the dopant as well as the overall extent of doping.

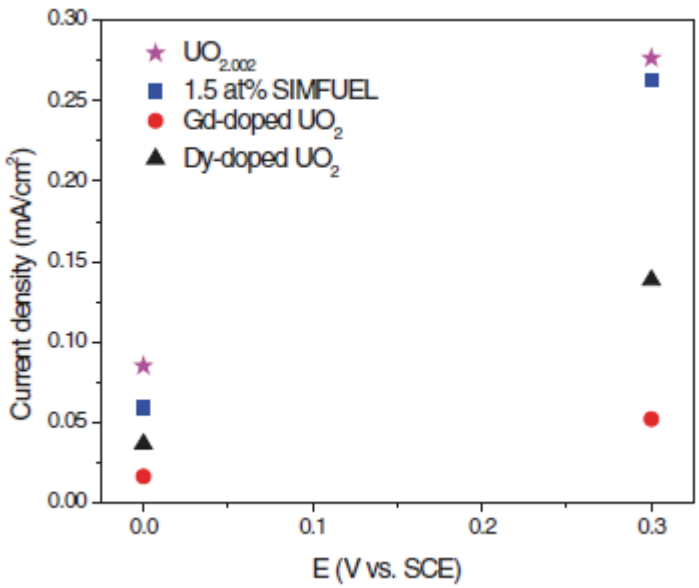


Figure 5.3: Anodic Currents Representing Oxidative Dissolution of UO_2, Recorded at 0 and 0.3 V on Four UO_2 Electrodes in Ar-purged 0.1 mol/L NaCl Solution (pH = 9)

5.1.1.3 Hydrogen Peroxide Studies

Hydrogen peroxide, H_2O_2, which is formed by the alpha radiolysis of water, is the dominant oxidant in a failed used fuel container. Consequently, its behaviour is important for understanding the corrosion/dissolution behaviour of the used fuel.

In 2013, electrochemical studies (i.e., open-circuit corrosion potential measurements and cyclic voltammetry) of H_2O_2 oxidation (i.e., $H_2O_2 \rightarrow 0.5\ O_2 + H_2O$) on 1.5 wt% SIMFUEL were carried out in Ar-purged 0.1 mol/L NaCl solutions, in the pH range 9.5 to 12.6, with and without carbonate. The concentration of H_2O_2 used in these experiments ranged from 0 to 0.2 mol/L.

The experimental results indicated that at pH = 9.5, the increase of anodic current was marginal when compared to the background recorded at $[H_2O_2]$ = 0 mol/L. However, in more alkaline solutions, the oxidation currents were considerably larger than background levels. The increase in anodic current with pH was partially attributed to the acid-base property of H_2O_2 (i.e., $H_2O_2 = H^+ + HO_2^-$, with HO_2^- dominant for pH > 11.6), suggesting that HO_2^- is more readily oxidized than

H_2O_2. The reaction is also influenced by the composition of the UO_2 surface. The plateau of anodic current in the potential region 0.15 V to 0.30 V reflected the suppression of the H_2O_2 oxidation reaction by formation of a surface U^{VI} deposit.

In order to study the competition between anodic oxidation of H_2O_2 and anodic oxidation of UO_2, the uranium concentrations in solution were measured. The amount of dissolved uranium in solution was converted to the charge required for oxidation from UO_2 to UO_2^{2+}. The total anodic charge was obtained by integration of the anodic current. The difference between the charge required for oxidation of UO_2 and the total anodic charge was attributed to H_2O_2 oxidation (because the surface oxidation extent was negligible in this case). Experiments were performed in solutions with and without carbonate ($[H_2O_2]$ = 0.02 mol/L, pH = 11 and $[Na_2CO_3]$ = 0 or 0.05 mol/L). The results indicated that, when the UO_2 was anodically polarized at pH=11, the predominant anodic reaction (> 70% of the charge) was H_2O_2 oxidation instead of UO_2 oxidative dissolution. This suggests that, under natural corrosion conditions (i.e., in the absence of anodic polarization), H_2O_2 decomposition rather than UO_2 corrosion would be the dominant reaction.

Note that the anodic currents were about 10-fold higher in the solutions containing carbonate because carbonate prevents the formation of surface deposits.

5.1.1.4 Criticality

Nuclear criticality (i.e., a sustained nuclear chain reaction) requires a sufficient concentration and critical mass of fissile isotopes, the presence of moderators in a favorable geometry and the absence of neutron absorbers.

Due to its lack of enrichment, criticality of standard CANDU fuel cannot be achieved outside of a nuclear reactor – where it is maintained in a defined configuration surrounded by heavy water coolant and heavy water moderator. Post discharge, inadvertent criticality is similarly not anticipated due to the depletion of fissile isotopes and the accumulation of neutron absorbing fission products and actinides.

In 2013, work was initiated to rigorously determine and document the margin to criticality for a set of bounding operational and postclosure scenarios and configurations. In this program, MCNP is used to examine the criticality of the Mark I and Mark II container designs for intact and degraded fuel configurations. The adopted approach is consistent with the requirements of CNSC RD-327 Nuclear Criticality Safety (CNSC, 2010).

Preliminary results confirm that used fuel within the two container designs will remain well below the criticality threshold ($k_{eff} < 1$) for intact and degraded fuel configurations. Additional calculations examining the criticality of scenarios in which the containers fail and radionuclides migrate into the near field will be completed and documented in 2014.

5.1.1.5 Fuel Burnups and Power Ratings

Discharge burnup and maximum power rating are key parameters for used nuclear fuel in that they largely determine the inventory of radionuclides, as well as the fraction of fission products that are able to migrate to the fuel gap and grain boundaries.

In 2006, an Ontario Power Generation (OPG) report was issued that summarizes these data for fuel discharged from the Darlington, Pickering A and B, and Bruce A and B nuclear reactors during the period from 1970 to 2006 (Wilk and Cantello, 2006). This report presents frequency histograms for burnup and maximum power rating for each station, together with tables showing the maximum, median, 90th, 95th, and 99th percentile values.

In 2012, a work program was initiated to update this information by incorporating 2006-2012 data, and by including information for the Gentilly 2 and New Brunswick Power reactors. Figure 5.4 and Figure 5.5 summarise the information from this new work, the results of which were published in a 2013 technical report (Wilk, 2013).

5.1.2 Repository Modelling

The repository, or near-field, region includes the container, the surrounding buffer and backfill, other engineered barriers, and the adjacent host rock. Almost all radioactivity associated with the used fuel is expected to be isolated and contained within this area over the lifetime of the repository. On-going work with respect to repository safety in the near-field region is aimed at improving understanding of the transport-limiting processes around a failed container. Work on container corrosion models carried out under the Repository Engineering program is described in Section 3.2.2.

5.1.2.1 Failed Container Model

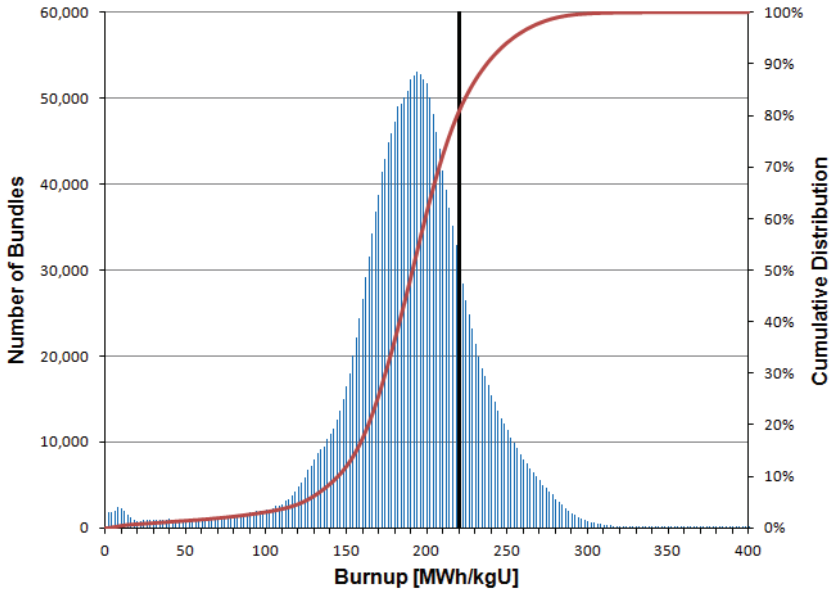
The used fuel container is a barrier to the release of radionuclides; it provides a barrier by preventing access of water to the used fuel. However, the containers will eventually corrode or fail, thereby allowing water to enter and contact the contents. Residual radioactivity within the used fuel may, thereafter, be released into the contact water due to a combination of instant release and slow dissolution.

For a copper container, the assumed non-corrosion failure mode is via a small weld defect that goes unnoticed during the fabrication and inspection processes. A 1/5000 defect frequency is assumed, with the failure being a small “pinhole”-like defect that extends through the copper shell.

As part of the exploration of options for sedimentary rock conditions (see Sedimentary Case Study, Section 5.2.2.2), containers made exclusively of steel are being considered also. These containers would be essentially identical to the reference copper containers, except the outer copper corrosion barrier would not be present. Because steel corrodes in the presence of water (or high humidity), it is anticipated that the containers will experience corrosion-related failures during the timeframe of interest. Such failures would not be consistent with the “pinhole” defect failure mode assumed for a copper container.

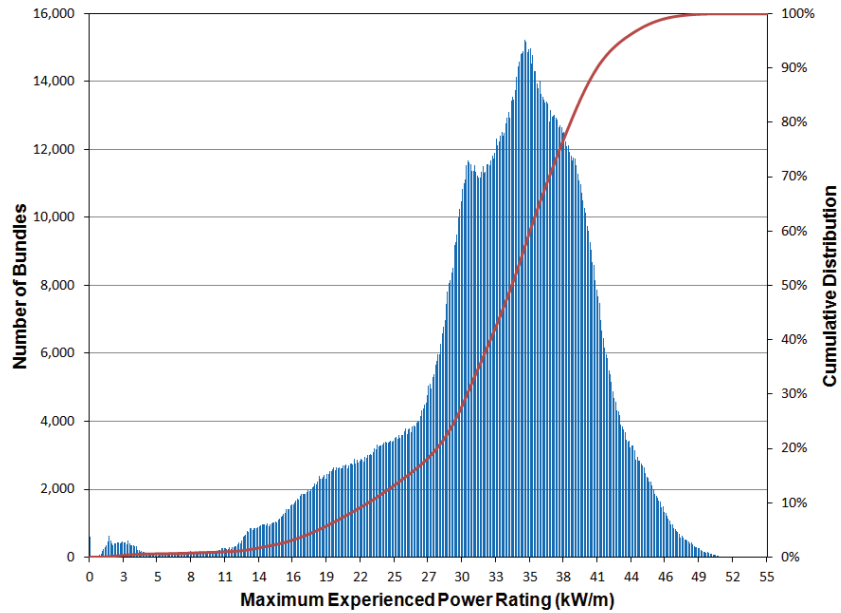
The COMSOL code has been used to model the radionuclide releases from a corroded container in a placement room. Results show that because the container is no longer an effective barrier:

- the flux of highly soluble elements is limited only by the fuel dissolution rate; and
- the flux of solubility-limited elements increases proportionally to the surface area through which radionuclides can diffuse.



Note: The reference 220 MWh/kgU is shown in black and the cumulative distribution is shown in red.

Figure 5.4: Distribution of Fuel Burnups for All Stations



Note: The cumulative distribution is shown in red.

Figure 5.5: Distribution of Power Rating for All Stations

This release model was used in the All Containers Fail Scenario in the pre-project report submitted to the CNSC (NWMO, 2013), illustrating postclosure safety of a used fuel repository in sedimentary rock (referred to herein as the Sedimentary Case Study, see Section 5.2.2.2). This release model will be used in future case studies whenever a failure mode different from a 'pinhole' defect is required. The model was summarized in Gobien and Garisto (2013).

5.1.2.2 Radionuclide Solubility

The maximum concentration of radionuclides is limited by their solubility in water. Many potentially important radionuclides, such as plutonium, have very low solubilities under the conditions expected at the repository horizon and will never mobilize in large amounts (note: under some groundwater conditions, colloid transport may be important).

Solubilities are generally calculated using thermodynamic models, which incorporate data for radionuclide elements as well as water composition and key minerals. There are a number of widely used thermodynamic datasets that support these models, and there is on-going international work to improve the data.

Throughout 2009 and 2010, the solubilities of several key radionuclides used in the safety assessment models were updated. Currently, both the Pitzer (Specific-ion Interaction) and SIT (Specific Ion Theory) approaches are used to calculate solubilities at high salinities. While the Pitzer approach is generally considered better at very high salinities, it currently has a more limited thermodynamic dataset. The Pitzer dataset from the Yucca Mountain Project Dataset, converted to PHREEQC format, was used to determine radionuclide solubilities. The SIT approach used the ThermoChimie v6 dataset developed by ANDRA (also in PHREEQC format).

The solubilities of Am, As, Bi, C, Cu, Mo, Nb, Np, Pa, Pb, Pd, Pu, Ra, Se, Sn, Tc, Th, U and Zr were calculated for reference crystalline (CR-10) and sedimentary (SR-270) water compositions. The interaction of the buffer materials and the container on the groundwater chemistry was included in the solubility calculations. Both the Pitzer and SIT approaches produced similar solubility results for elements found in both datasets (Duro et al., 2010).

No additional solubility work was completed in 2013; however, additional calculations for other highly saline brine compositions may be carried out in support of postclosure safety case studies for sedimentary rock geospheres in the future. Because such calculations would benefit from the availability of a thermodynamic database appropriate for the conditions existing in Canadian groundwaters, efforts are now focused on developing such a database (refer to Section 5.1.2.3).

5.1.2.3 Thermodynamic Database Review

NWMO continues to support the joint international Nuclear Energy Agency (NEA) effort on developing thermodynamic databases for elements of importance in safety assessment (Mompeán and Wanner, 2003). Phase III of the Thermochemical Database (TDB) Project was completed in 2013 with the publication of the volumes describing the thermodynamic data for tin and iron (Part 1) (Gamsjäger et al., 2012; Lemire et al., 2013). Phase IV, initiated in February 2008, focuses on compilation and review of thermodynamic data for molybdenum and iron (Part 2), review of thermodynamic data for auxiliary species, and initiation of state-of-the-art reports on cements. An initiation report on the thermodynamic data for cement materials was

completed in 2013 (Blanc et al., 2013). Based on this report, a project to prepare a state-of-the-art report on cement minerals was approved. Phase V was initiated in 2013 (see below), and Phase IV activities that were not completed have been moved into Phase V.

Phase V of the TDB Project was defined with two primary objectives: 1) updating the Phase II actinide thermodynamic databases, including technetium; and 2) preparation of state-of-the-art reports on thermodynamic considerations for cement materials, thermodynamic considerations for actinide elements in high ionic strength aqueous solutions, and thermochemical extrapolation of data to non-standard state temperatures. Phase V will officially commence after all the participating organizations have signed the Phase V agreement.

The NEA TDB project provides high-quality datasets for a limited number of elements. This information is important, but is not sufficient on its own, as it does not address the full range of elements of interest. Also, the NEA TDB has, until recently, focused on low salinity systems. Due to the high salinity of brines observed in sedimentary and crystalline rocks in Canada, a thermodynamic database including ion interaction parameters is needed for radionuclide solubility calculations.

An evaluation of the Yucca Mountain Pitzer database, data0.ypf.R2, was conducted in 2012 in terms of comprehensiveness, consistency and accuracy, with emphasis on the comparison of the Pitzer model to the experimental data (e.g., solubility, activity and deliquescence relative humidity). Recommendations were made to develop a new Pitzer database that is internally consistent and suitable for Canadian geology. Contact was made in 2012 with a German working group (Altmaier et al., 2011) developing a new database: the THEREDA (THErmodynamic Reference Database) Pitzer thermodynamic database. A review of the first and third releases of THEREDA, which primarily focus on the model for the oceanic salt system, was conducted in 2013 to compare the THEREDA Pitzer model with experimental data and other models. In 2014, the results of the review will support the decision on whether THEREDA can form the basis of a NWMO Pitzer thermodynamic database.

5.1.2.4 Gas Transport through Buffer

Corrosion of steel in the repository will result in the slow generation of gases. The low-permeability saturated clay seal around the container will retain these gases until a threshold pressure is reached, after which the gases will escape. This is of interest for understanding behaviour in the near-field around a failed container. To explore these processes, a full-scale in-situ test, LASGIT, was initiated several years ago in the SKB Äspö Hard Rock Laboratory in Sweden. NWMO is contributing to the gas transport modelling component of this project.

Version 2.0 of TOUGH2, a two-phase flow code, was selected and modified for LASGIT to simulate pressure-induced changes in properties, such as pore dilation. In 2006 and 2007, the modified code was applied to laboratory experimental data (MX-80-10 conducted by Harrington and Horseman, 2003) and predictive simulations of the LASGIT experiment. Results of the preliminary gas tests performed in 2008 at LASGIT (Gas Test 1) were analysed in 2009. The results seemed to indicate that gas dilation had occurred; however, a response to the gas dilation was not observed at any of the pressure sensors in the experiment. In 2011, 3D simulations were generated for Gas Test 2 (executed in 2009), which showed complex gas propagation behaviour in still partially saturated bentonite. The modelling was promising in its ability to represent gas breakthrough at the injection port; however, model gas propagation was

too slow and diffuse, with gas appearing at the rock wall at a location in the model different from that in the experiment.

In 2012/2013, further modelling of Gas Test 2 was conducted, using additional information and data. Experimental data obtained after Gas Test 2 suggests that all pressure responses observed during Gas Test 2 occurred at the bentonite-container interface. Analysis of Gas Test 3 data (conducted in 2010), which hydraulic test data indicates to be fully water-saturated, similarly shows all responses occur at the bentonite-container interface, as illustrated in Figure 5.6. The focus of modelling Gas Tests 2 and 3, therefore, shifted towards the bentonite-container interface and included modifications to the pressure-dependent permeability functions to improve the model's ability to simulate a distinct pathway. A technical report will be issued in 2014 to document the LASGIT modelling work.

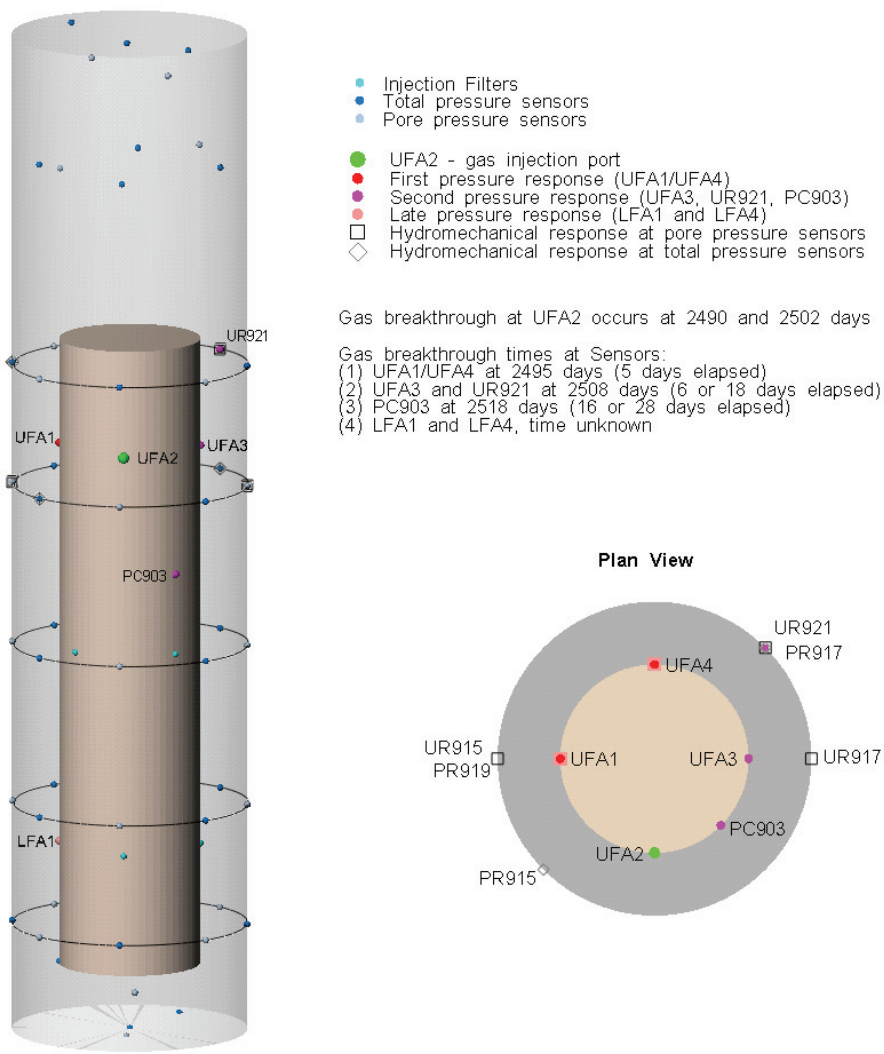


Figure 5.6: SKB LASGIT Gas Test 3 (2010 Gas Injection Tests) Showing Locations of Gas Injection (UFA2) and Gas Breakthrough

5.1.2.5 Gas-Permeable Seal Test

The purpose of a gas-permeable seal is to enhance gas transport through the backfilled excavations of the deep geological repository without undermining the ability of the engineered barrier system or the host rock to contain the radioactivity of the used nuclear fuel. NAGRA has proposed a gas-permeable seal as part of an Engineered Gas Transport System, comprised of specially designed sealing materials such as a 70/30 (wt%) bentonite/sand mixture.

In support of this work, the Gas-Permeable Seal Test (GAST) was constructed at the Grimsel Test Site in order to:

- confirm effective functioning of gas-permeable seals on physically relevant scales;
- validate and potentially improve existing conceptual models for resaturation and gas transport;
- calculate two-phase flow parameters;
- assess in-situ emplacement techniques and associated quality assurance measures; and
- develop non-destructive monitoring systems.

In 2013, the NWMO provided funding in support of GAST.

5.1.2.6 Shaft Seal Properties

The shaft seal for a deep geologic repository will include various materials with different functions. The reference materials are 70/30 (wt%) bentonite/sand mixture, Low-Heat High-Performance Concrete (LHHPC), and asphalt.

In 2011, NWMO initiated a series of basic physical and mechanical tests on 70/30 bentonite-sand shaft seal material in order to establish the effect of groundwater salinity on its behaviour. The tests evaluated the following:

- density of as-fabricated material
- porosity of as-fabricated material
- moisture content of as-fabricated material
- chemical composition of as-fabricated material
- swelling pressure under various reference groundwater conditions
- saturated hydraulic conductivity under various reference groundwater conditions
- gas permeability
- mechanical properties

Two independent laboratories were retained to carry out the analyses. The data reported by AECL is presented in Priyanto et al. (2013), and is summarized below in Table 5.2.

Analyses by Golder used larger sample sizes in comparison to the AECL program, resulting in longer saturation times. The majority of tests are complete and receipt of the final data reports will occur in 2014.

The saturated hydraulic conductivity and swelling pressures reported by the two independent laboratories are also presented as a function of the Effective Montmorillonite Dry Density (EMDD). The 70/30 bentonite-sand results for swelling pressure in fresh water conditions are

shown in Figure 5.7, along with data summarized from a literature review, and the best fit line presented by Baumgartner (2006). The results for hydraulic conductivity as a function of EMDD are presented in Figure 5.8. The results suggest that the test results for hydraulic conductivity and swelling pressure are in accordance with values predicted by fitted lines, as described by Baumgartner (2006).

Table 5.2: Properties of 70-30 Bentonite-Sand Mixture (BSM)

Tests	Properties	Pore liquid Type			
		DW	CR10	SR160	SR270
Free swell tests	Free Swell Index (FSI) (mL/2g)	9.0	7.3	4.3	3.5
Consistency (Atterberg) Limits	Liquid limit, LL (%)	341	124	51	30
	Plastic limit, PL (%)	31	30	26	24
	Plasticity Index, PI (%)	309	94	24	8
Compaction properties (Proctor)	Maximum dry density (Mg/m^3)	1.83	1.83	1.86	1.86
	Optimum moisture content-corrected due to salt (OMC') (%)	16	16	16	16
Liquid Hydraulic Conductivity & Swelling Pressure	Saturated Hydraulic Conductivity, $k_{w\text{-}sat}$ (m/s) at 1.8 Mg/m^3 dry density	$1.5x10^{-13}$	$1.4x10^{-13}$	$5.6x10^{-13}$	$2.6x10^{-12}$
	Swelling Pressure, Ps (MPa) at 1.8 Mg/m^3 dry density	4.6	3.8	1.2	1.1
Gas Permeability	Gas permeability, k_g (m/s), at 1.8 Mg/m^3 dry density and 85% S_w	$6x10^{-14}$	$8x10^{-13}$	$2x10^{-12}$	$8x10^{-12}$

In 2012, NWMO initiated a series of basic physical and mechanical tests on the LHHPC and asphalt-based material to establish baseline properties and also to determine the effect of high groundwater salinity on their behaviour.

Initial tests on the LHHPC and asphalt–based materials were carried out under distilled water and water with salinity of 270 g/L. The test result indicates that the LHHPC and asphalt-based samples have very low porosity and very low saturated hydraulic conductivity (< 10^{-13} m/s) under the two reference waters. Figure 5.9 shows the change in unconfined compressive strength of LHHPC samples with curing age. At 270 days of curing, the unconfined compressive strength of these samples approaches 95-100 MPa. These initial tests show that the LHHPC and asphalt-based materials can provide a low hydraulic permeability barrier to groundwater movement. In addition, LHHPC can provide good mechanical support to overlying materials.

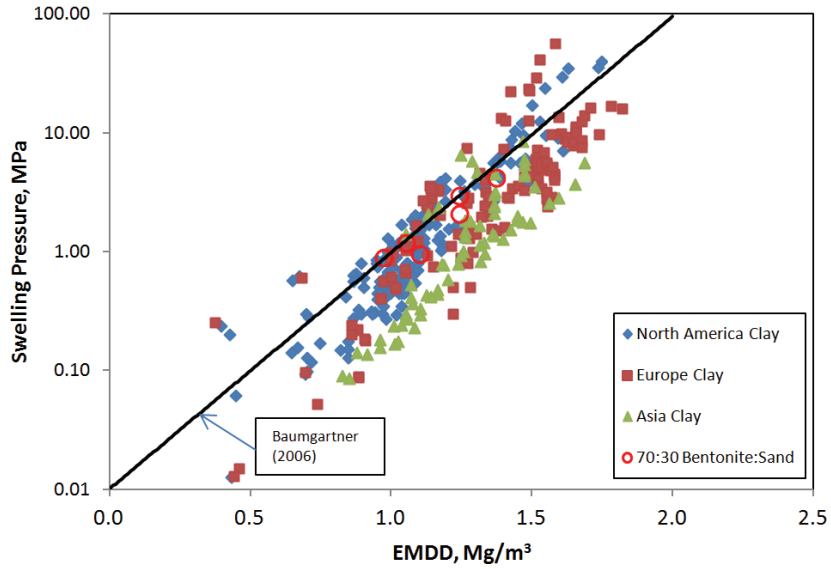


Figure 5.7: Swelling Pressure as a Function of Effective Montmorillonite Dry Density for Bentonite Clays at Fresh Water Conditions

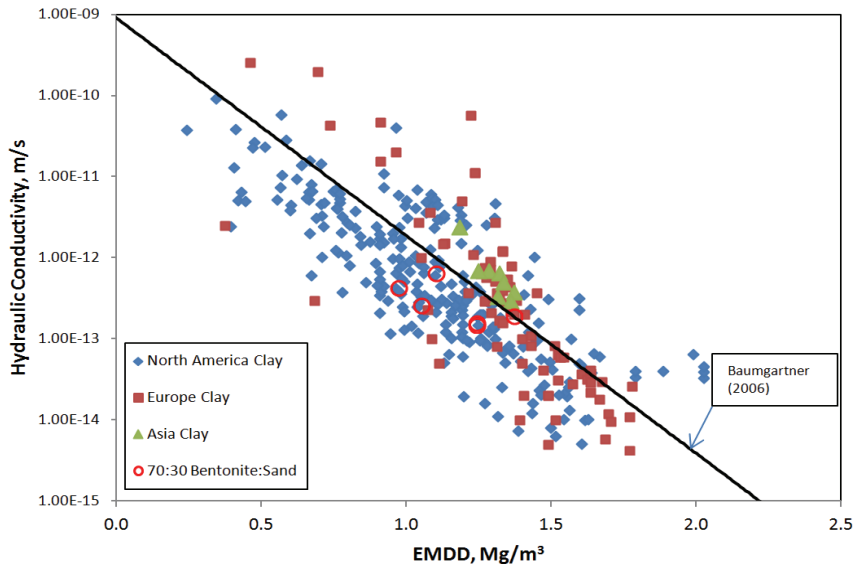


Figure 5.8: Hydraulic Conductivity as a Function of Effective Montmorillonite Dry Density for Bentonite Clays at Fresh Water Conditions

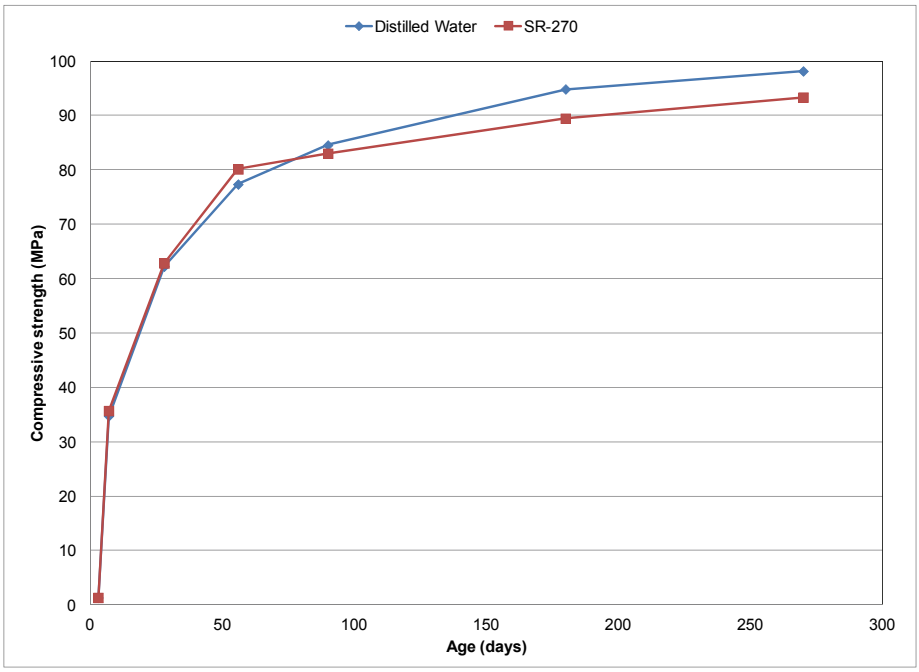


Figure 5.9: Unconfined Compressive Strength Results for LHHPC

5.1.3 Geosphere Modelling

5.1.3.1 Probabilistic FRAC3DVS-OPG and SYVAC3-CC4 Modelling

Safety assessments conducted by the NWMO use the following two computer codes.

- FRAC3DVS-OPG: used to generate detailed 3D deterministic finite-element predictions of groundwater flow and transport for a limited number of cases and for a limited number of radionuclides. Run times are quite long (hours to days) and the absence of a biosphere model means dose predictions cannot be obtained.
- SYVAC3-CC4: used to generate deterministic and probabilistic predictions of radionuclide releases to the environment. Run times are quite short (5 minutes) and a large number of radionuclides can be represented. A biosphere model is available and dose predictions can be obtained.

The SYVAC3-CC4 model is simplified and approximate when compared to the more sophisticated FRAC3DVS-OPG code; however, the long run times associated with the FRAC3DVS-OPG model preclude the use of this tool for probabilistic studies where, typically, 120,000 simulations are performed. With the advent of relatively inexpensive processing power and cluster or parallel computing, running detailed models probabilistically is becoming more feasible.

A work program was initiated in 2012 to test, using a proof-of-concept approach, the feasibility of conducting probabilistic simulations using detailed 3D numeric models. Existing models used in the safety assessment case study for a conceptual repository in crystalline rock (NWMO, 2012a) have been simplified and the modelling workflow automated to allow complete simulations to be executed under the control of a probabilistic sampling executive.

The results of this study (Avis and Sgro, 2013) indicate that it might be feasible to use FRAC3DVS-OPG for probabilistic studies. An expansion of this work program (specifically, performing probabilistic assessments of a coupled geosphere-biosphere model) is under review for 2014.

5.1.4 Biosphere Modelling

5.1.4.1 Non-Human Biota

In 2008, a screening methodology was developed for assessing the potential postclosure impact of a repository on specific representative non-human biota. The methodology involved the estimation of reference No-Effect Concentrations (NECs) for radionuclides in environmental media to which biota are exposed. Because of the conservative nature of the assumptions used to derive NECs, there was confidence that, despite uncertainty in environmental concentrations, there would be no significant ecological effect on biota as long as the NECs were not exceeded. The NECs were developed for a set of 12 radionuclides, including the major dose contributors identified in the Canadian Third Case Study and other safety assessments. The NEC approach is also used in the most recent safety assessment for a conceptual repository in crystalline rock (NWMO, 2012a).

In Europe, the calculation of dose consequences to non-human biota is largely performed using the ERICA approach (e.g., Torudd and Facilia, 2010). One of the significant differences between ERICA and the NECs is the approach used to model the partitioning behaviour of a radionuclide between the media and the organism. ERICA uses concentration ratios, which estimate the concentration in an organism based on the concentration in the media (soil or water) in which it exists. The NEC approach uses transfer factors, which estimate the concentration in an organism based on the intake rate (of food, soil, water or sediment).

In 2012, the NWMO developed a non-human biota dose assessment model, which separately calculates dose consequences using the transfer factor approach (as with the NECs) and concentration ratio approach (as in the ERICA tool). The model considers the effects of 45 radionuclides on a wide range of species that are representative of the main taxonomic groups found in 3 different Canadian ecosystems (the southern Canadian Deciduous forest, the boreal forest and the inland tundra). A technical report documenting the approach will be published in 2014.

Because the topic of dose consequences to non-human biota is of current international and regulatory interest, NWMO will continue to monitor and conduct work activities in this area in upcoming years.

5.1.4.2 Aboriginal Lifestyle Characterization

The interests and concerns of Aboriginal peoples, as they pertain to a used fuel deep geological repository, are an integral part of the NWMO work program. Previous Canadian postclosure safety assessments have calculated doses to a hypothetical self-sufficient farming household living in the vicinity of the repository under temperate boreal conditions. Recognizing the need to consider time scales up to 1 million years, alternative exposure groups, with other diets and lifestyles, should be considered to ensure comprehensiveness of the safety assessment.

In 2013, work was initiated to update existing Aboriginal lifestyle characterization data, representative of the Boreal Forest and Inland Tundra, and to develop new data to characterize the Aboriginal lifestyle in the Southern Canadian Deciduous Forest. Key non-human biota species of importance to aboriginal communities are also to be identified. Results of this study have been reviewed by the Assembly of First Nations (AFN). A technical report, incorporating feedback from the AFN review, will be issued in 2014.

5.1.4.3 Participation in BIOPROTA

BIOPROTA is an international collaborative program created to address key uncertainties in long-term assessments of contaminant releases into the environment arising from radioactive waste disposal. Participation is aimed at national authorities and agencies with responsibility for achieving safe and acceptable radioactive waste management practices, including both regulators and operators. Overall, the intention of BIOPROTA is to make available the best sources of information to justify modelling assumptions made within radiological assessments constructed to support radioactive waste management.

C-14 Project

In 2013, a review of the C-14 dose assessment models was completed. Models for C-14 dose assessment have been under review in the BIOPROTA work program since 2005. The last review, which was completed in 2011, concluded that that the conceptualization of the dynamics of the plant canopy atmosphere influenced the calculated plant C-14 concentrations. Work done in 2012 and 2013 sought to further understanding of carbon biogeochemistry. A paper was accepted for publication in the Radiocarbon Journal (Mobbs et al., 2013) and a workshop was held to further the collective understanding of different approaches for modelling.

This project was financially supported by the NWMO, together with ANDRA and EDF (France), BfS (Germany), EPRI (USA), NAGRA and ENSI (Switzerland), NDA RWMD (UK), NUMO (Japan), POSIVA (Finland), SKB and SSM (Sweden).

Scales of Post-closure Assessment Scenarios (SPACE)

The purpose of this work program is to examine the effect of temporal and spatial scales when assessing the postclosure radiological impacts of radioactive waste repositories on representative wildlife species. The variety of plants and animals in the natural environment is immense and, as such, the scope of the project has necessarily been limited to the general types of plants and animals representative of temperate terrestrial ecosystems. A report on this work is expected to be published in early 2014.

This project is financially supported by the NWMO, together with ANDRA and EDF (France), RWMD/NDA (UK), NAGRA (Switzerland), NUMO (Japan), POSIVA (Finland), SKB and SSM (Sweden).

Geosphere-Biosphere Interface Project

This work program is designed to develop an improved and structured approach to characterizing and representing the interface between the geosphere and biosphere in long-term radiological impact assessment models. Various scenarios of interest are developed and used to explore issues that arise in characterising the interface between the geosphere and the biosphere. It is recognised that the geosphere-biosphere interface has not previously been well defined and that the appropriate characterization may differ in alternative assessment contexts. Thus, a scenario-based approach is being adopted, followed by conceptual modelling and an investigation of the various mathematical models that are available to explore and evaluate the processes and their interactions identified in the conceptual modelling. The results from this work will be issued in a project report in 2014.

This project currently is financially supported by the NWMO, together with ANDRA and EDF (France), RWMD/NDA (UK), NUMO (Japan), SKB and SSM (Sweden).

5.1.5 System Modelling

The postclosure safety assessment of a used fuel repository uses several complementary computer models, as identified in Table 5.3. These are either commercially maintained codes, or codes maintained by the NWMO software quality assurance program.

Table 5.3: Main Safety Assessment Codes for Preclosure and Postclosure Analyses

Software	Version	Description / Use
SYVAC3-CC4	9.1	Reference integrated system model
FRAC3DVS-OPG	1.3	Reference 3D groundwater flow and transport code
T2GGM	3.1	3D two-phase gas and water flow code
AMBER	5.6	Generic compartment modelling software
COMSOL	4.3a	3D multi-physics finite element modelling software
PHREEQC	3.0.6	Geochemical calculations code
MICROSHIELD	9.05	Radioactive shielding and dose code
ORIGEN (SCALE)	4.2	Used fuel inventory calculations
MCNP	5.0	Criticality and shielding assessments

The following sections describe code-related activities conducted in 2013.

5.1.5.1 Updates to SYVAC3-CC4

There were two software updates to the integrated system model SYVAC3-CC4 in 2013.

The first update was a minor revision to the code and updated SYVAC3-CC4 to version 9.1. The purpose of this update was to address a minor error identified during the Sedimentary Case Study (see Section 5.2.2.2). Changes to the code corrected a bug in the geosphere response function with a zero concentration boundary condition. This module had not been used in several years and was calling an outdated function, resulting in an error in certain situations. The update to SYVAC3-CC4 v9.1 was very minor and did not constitute a brand new release. As such, the majority of the SYVAC3-CC4 v9 documentation (NWMO, 2012b) still applies to version 9.1.

The second set of updates was initiated at the end of 2013 and will continue through mid-2014. The new version of SYVAC3-CC4 will be version 10. The purpose of this update is to add several additional code features and correct minor errors (e.g., malformed output for some parameters). New SYVAC3-CC4 v10 code features will include:

- consistent handling of biosphere degassing and deposition pathways;
- additional biosphere plant types;
- a new leaching wasteform;
- time dependence to the defect size;
- a new simplified well model;
- an updated gas transport model; and
- updated geosphere and near field sorption models.

The SYVAC3-CC4 Fifth Case Study dataset was issued in 2013 (Gobien et al., 2013). This dataset includes the following revisions:

- a new sedimentary geosphere (GEONET) model;
- new materials within the input data corresponding to the various sedimentary rock formations;
- new data for the physical (e.g., porosity) and chemical (e.g., sorption) properties of the sedimentary rock layers;
- new data for the highly saline sedimentary groundwater (e.g., solubilities); and
- changes to the biosphere data to better represent a generic southern Ontario site being considered as part of that study.

The on-going SYVAC3-CC4 validation efforts were documented in a new report (Garisto and Gobien, 2013). Existing validation tests that no longer apply to the current version of SYVAC3-CC4 were removed and new validation tests were incorporated, including.

- further validation of the used fuel dissolution model against laboratory experiments
- additional validation of the SYVAC3-CC4 container release model via comparison with COMSOL
- additional validation of the SYVAC3-CC4 near field model via comparison with COMSOL
- validation of the response function solution for a diffusive geosphere via comparison with FRAC3DVS-OPG and COMSOL
- additional verification of the “GEONET” geosphere modelling approach performed by comparing SYVAC3-CC4 and FRAC3DVS-OPG modelling results
- verification of the SYVAC3-CC4 glaciation model via comparison with FRAC3DVS-OPG results

Validation of the SYVAC3-CC4 code will continue as an on-going effort.

5.1.5.2 Updates to T2GGM

T2GGM (TOUGH2 with Gas Generation Modelling) is a three-dimensional, two-phase, gas and groundwater flow code maintained by the NWMO. The following updates were under development in 2013.

- Implementation of pressure-dependent permeabilities, based on a predefined, static stress field
- Integration of T2GGM with FLAC3D for poroelastic coupling of stress and pore pressure through porosity, as well as permeability-response to rock damage as a function of stress, pore pressure, and material properties

Issuing a revised version of the T2GGM code will depend on a review of the modelling results, as well as compliance with NWMO software quality assurance requirements,

Evolution of gas within repositories under postclosure conditions is expected to remain an important part of postclosure safety assessment. The T2GGM code will continue to be developed in 2014.

5.1.5.3 Updates to Miscellaneous Codes

New versions of a few commercially available codes were also released in 2013 and installed on safety assessment computers, including AMBER v5.6 and PHREEQC v3.0.6.

5.2 SAFETY STUDIES

The objective of safety case studies is to provide illustrative examples of repository safety under various conditions, and to test and/or demonstrate NWMO's safety assessment approach.

The focus of these studies is primarily on the postclosure period; however, some work activities on the preclosure period are also underway. The following sections describe work undertaken in both of these subject areas.

5.2.1 Preclosure Studies

5.2.1.1 Container Dose Calculations

This study characterizes the neutron and gamma dose components from various used fuel bundle and container shielding configurations using Monte Carlo N-Particle (MCNP) modelling. The purpose of the study is to provide benchmark dose rates for simple geometries and shielding configurations.

The calculations were divided into a series of cases with varying configurations of sources (fuel bundle, IV-25 container and Mark II container), fuel age (10y and 30y), burnup (220 MW/kgU and 280 MW/kgU), shielding material (air, bentonite, crystalline rock, concrete, water, steel and

polyethylene), shielding thicknesses, distances from source (contact to 100 meters) and source locations (floating in air or resting on concrete). Results of this work provide dose estimates supporting:

- engagement activities, because questions about the nature of the hazard are often posed in specific terms by members of the public; and
- engineering activities, because shield thicknesses are required for design optimization.

5.2.2 Postclosure Studies

5.2.2.1 NEA FEPS Update

Features, Events and Processes (FEPs) provide a brief screening analysis for each performance assessment factor, indicating whether or not it should be included within the detailed safety assessment. Development of an internationally recognized FEPs database is useful in that it helps ensure the NWMO FEPs are consistent with international best practices.

In accordance with a decision made at the 2013 Integration Group for Safety Case (IGSC) annual meeting, the NEA accepted the proposed work activities to further develop the FEP database. In 2013, the NWMO provided funding to support this activity.

5.2.2.2 Sedimentary Case Study

In 2013, a pre-project report was submitted to the CNSC (NWMO, 2013) providing an illustrative postclosure safety assessment for a used fuel repository in sedimentary rock (referred to herein as the Sedimentary Case Study). The NWMO's primary objective for the pre-project review is to confirm that the safety assessment is consistent with CNSC Guide, G-320, on "*Assessing the Long Term Safety of Radioactive Waste Management"* (CNSC, 2006).

The Sedimentary Case Study builds on a series of postclosure safety assessments for a deep geological repository in crystalline rock. Key differences relative to the previous Case Study are an updated reference repository layout, the use of in-room container placement, and an updated reference geosphere, such as could be encountered on the margin of the Michigan Basin in southern Ontario.

Also, the FEPS database was reorganized and updated to reflect current knowledge and to adopt interim revisions to the NEA International FEPs list. New FEPs screening analyses were developed in support of performance assessments within a sedimentary geosphere, reflecting the reference repository design and biosphere.

The used fuel container is assumed to consist of an outer copper vessel, an inner steel vessel, and three steel baskets. The copper vessel provides a corrosion-resistant barrier in the repository environment. The inner vessel is designed to withstand any mechanical stresses, including stresses due to glaciation. Each container has the capacity to contain 360 used fuel bundles.

Once placed in the repository, the containers are surrounded by compacted bentonite clay. All excavated spaces are filled with mixtures of clay, sand and rock to minimise the flow of water.

In addition, placement rooms are sealed with bulkheads of special high-performance concrete. Shafts are similarly filled and sealed, isolating the repository from the biosphere.

The geosphere represents one example of a possible sedimentary rock setting in southern Ontario, providing the information necessary to support an illustrative safety assessment.

The study considers both Normal Evolution and Disruptive Event scenarios, together with a range of associated sensitivity studies performed to illustrate the sensitivity of results to assumed degradations in the engineered and natural barriers. The results of both deterministic and probabilistic simulations are presented.

The work program resulted in the production of two auxiliary technical reports issued to support the postclosure safety assessment:

- Reference Data and Codes (Gobien et al., 2013); and
- Features, Events and Processes (Garisto, 2013).

The results indicate that, for the case considered, the radiological and non-radiological interim acceptance criteria could be met during the postclosure period. This is consistent with previous assessments of a deep geological repository in Canada, as well as with safety assessment studies by other national radioactive waste management organizations.

REFERENCES

Altmaier, M., V. Brendler, C. Bube, V. Neck, C. Marquardt, H.C. Moog, A. Richter, T. Scharge, W. Voigt, S. Wilhelm, T. Willms and G. Wollmann. 2011. THEREDA Thermodynamische Referenz-Datenbasis. Abschlussbericht (dt. Vollversion), 863p.

Avis, J. and N. Sgro. 2013. Probabilistic Safety Assessment using Detailed Groundwater Flow and Transport Models. Nuclear Waste Management Organization Technical Report NWMO TR-2013-09. Toronto, Canada.

Baumgartner, P. 2006. Generic Thermal-Mechanical-Hydraulic (THM) Data for Sealing Materials - Volume 1: Soil – Water Relationships". Ontario Power Generation Report 06819-REP-01300-10122-R00.

Bea Jofre, S.A., K.U. Mayer and K.T.B. MacQuarrie. 2011. Modelling Reactive Transport in Sedimentary Rock Environments – Phase II, MIN3P Code Enhancements and Illustrative Simulations for a Glaciation Scenario. Nuclear Waste Management Organization Technical Report NWMO TR-2011-13. Toronto, Canada.

Birch, K., M. Ben Belfadhel, J. Freire-Canosa, F. Garisto, P. Gierszewski, M. Hobbs, T. Kempe, G. Kwong, T. Lam, P. Lum, P. Maak, S. Russell and A. Vorauer. 2008. Technical research and development program for long-term management of Canada's used nuclear fuel – Annual report 2007. Nuclear Waste Management Organization Report NWMO TR-2008-01. Toronto, Canada.

Blanc, P., B. Lothenbach, J. Perrone and B. Schwyn. 2013. NEA TDBIV project: preparation of a state-of-the-art report on thermodynamic data for cement. In 3rd International Workshop: Mechanisms and Modelling of Waste/Cement Interactions. Ghent, Belgium.

Cavé, L., T. Al, Y. Xiang and P. Vilks. 2009a. A technique for estimating one-dimensional diffusion coefficients in low-permeability sedimentary rock using X-ray radiography: Comparison with through-diffusion measurements. Journal of Contaminant Hydrology, 103, 1-12.

Cavé, L.C., T. Al and Y. Xiang. 2009b. X-ray radiography techniques for measuring diffusive properties of sedimentary rocks. Nuclear Waste Management Organization Technical Report NWMO TR-2009-03. Toronto, Canada.

Cavé, L., T. Al, Y. Xiang and D. Loomer. 2010. Investigations of Diffusive Transport Processes in Sedimentary Rock. Nuclear Waste Management Organization Technical Report NWMO TR-2010-04. Toronto, Canada.

Clark, I., R., H. Mohapatra, H. Mohammadzadeh and T. Kotzer. 2010a. Pore Water and Gas Analyses in DGR-1 and DGR-2 Core. Intera Engineering Ltd. Report TR-07-21. Ottawa, Canada.

Clark, I., I. Liu, H. Mohammadzadeh, P. Zhang, R. Mohapatra and M. Wilk. 2010b. Pore Water and Gas Analyses in DGR-3 and DGR-4 Core. Intera Engineering Ltd. Report TR-08-19. Ottawa, Canada.

Clark, I., V. Scharf, J. Zuliani and M. Herod. 2011. Technical Report: Pore Water Analysis in DGR-5 and DGR-6 Core. Intera Engineering Ltd. Report TR-09-04. Ottawa, Canada.

CNSC. 2006. Guide G-320: Assessing the Long Term Safety of Radioactive Waste Management. Canadian Nuclear Safety Commission. Ottawa, Canada.

CNSC. 2010. Regulatory Document RD-327: Nuclear Criticality Safety. Canadian Nuclear Safety Commission. Ottawa, Canada.

Crowe, R., K. Birch, J. Chen, D. Doyle, F. Garisto, M. Gobien, N. Hunt, S. Hirschorn, M. Hobbs, P. Keech, L. Kennell, E. Kremer, P. Maak, J. McKelvie, C. Medri, M. Mielcarek, A. Murchison, A. Parmenter, R. Ross, E. Sykes and T. Yang. 2013. Technical Program for Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2012. Nuclear Waste Management Organization Report NWMO TR-2013-01. Toronto, Canada.

Davis, D. 2013. Application of U-Pb Geochronology Methods to the Absolute Age Determination of Vein Calcite. Nuclear Waste Management Organization Technical Report NWMO TR-2013-21 (In progress).

Delaloye D, M.S. Diederichs, G. Walton and J. Hutchinson. 2014. Sensitivity testing of the newly developed elliptical fitting method for the measurement of convergence in tunnels and shafts. Rock Mech Rock Eng, online, 15 March 2014.

Diederichs, M.S. 2007. The 2003 Canadian Geotechnical Colloquium. Mechanistic Interpretation and Practical Application of Damage and Spalling Prediction Criteria for Deep Tunneling. Canadian Geotechnical Journal 44, 1082-1116.

Duro, L., V. Montoya, E. Colas and D. Garcia. 2010. Groundwater Equilibration and Radionuclide Solubility Calculations. Nuclear Waste Management Organization Report NWMO TR-2010-02. Toronto, Canada.

Eichinger, F. and H.N. Waber. 2013. Matrix Porewater in Crystalline Rocks: Extraction and Analysis. Nuclear Waste Management Organization Technical Report NWMO TR-2013-23. Toronto, Canada.

Eriksen, T.E., D.W. Shoesmith and M. Jonsson. 2012. Radiation induced dissolution of UO2-based nuclear fuel – A critical review of predictive modelling approaches. J. Nucl. Mater. 420, 409-423.

Fracture Systems LTD. 2011. Excavation Damaged Zones Assessment. Fracture Systems Ltd. report for the Nuclear Waste Management Organization Technical Report NWMO DGR-TR-2011-21 R000. Toronto, Canada.

Gamsjäger, H., T. Gajda, J. Sangster, S.K. Saxena and W. Voigt. 2012. Vol. 12. Chemical Thermodynamics of Tin, OECD Nuclear Energy Agency Data Bank. (Eds.), OECD Publications. Paris, France.

Garisto, F. 2000. Used fuel disposal technology program: listing of technical reports. Ontario Power Generation, Nuclear Waste Management Division Report 06819-REP-01200-10032-R00. Toronto, Canada.

Garisto F. and M. Gobien. 2013. SYVAC3-CC4 Verification and Validation Summary. Nuclear Waste Management Organization Technical Report NWMO TR-2013-14. Toronto, Canada.

Garisto, F. 2013. Fifth Case Study: Features, Events and Processes. Nuclear Waste Management Organization Technical Report NWMO TR-2013-06. Toronto, Canada.

Ghazvinian, E., M. Perras, C. Langford, M. Diederichs, and D. Labrie. 2013. A comprehensive investigation of crack damage anisotropy in Cobourg limestone and its effect on the failure envelope. Proceedings of GeoMontreal 2013 – Canadian Geotechnical Society Conference. Montreal, Canada.

Gierszewski, P.J., S.B. Russell, F. Garisto, M.R. Jensen, T.F. Kempe, P. Maak and G.R. Simmons. 2001. Deep Geologic Repository Technology Program - Annual Report 2000. Ontario Power Generation, Nuclear Waste Management Division Report 06819-REP-01200-10055-R00. Toronto, Canada.

Gierszewski, P.J., S.B. Russell, F. Garisto, M.R. Jensen, T.F. Kempe, P. Maak, G.R. Simmons and A. Vorauer. 2002. Deep Geologic Repository Technology Program - Annual Report 2001. Ontario Power Generation, Nuclear Waste Management Division Report 06819-REP-01200-10080-R00. Toronto, Canada.

Gierszewski, P.J., S.B. Russell, A. D'Andrea, F. Garisto, M.R. Jensen, T.F. Kempe, P. Maak, G.R. Simmons and A. Vorauer. 2003. Deep Geologic Repository Technology Program - Annual Report 2002. Ontario Power Generation, Nuclear Waste Management Division Report 06819-REP-01200-10100-R00. Toronto, Canada.

Gierszewski, P.J., S.B. Russell, A. D'Andrea, F. Garisto, M. Hobbs, M.R. Jensen, T.F. Kempe, P. Maak, G.R. Simmons and A. Vorauer. 2004. Deep Geologic Repository Technology Program - Annual Report 2003. Ontario Power Generation, Nuclear Waste Management Division Report 06819-REP-01200-10129-R00. Toronto, Canada.

Gobien, M., F. Garisto, and E. Kremer. 2013. Fifth Case Study: Reference Data and Codes. Nuclear Waste Management Organization Technical Report NWMO TR-2013-05. Toronto, Canada.

Guo, R. 2014. One-Dimensional Coupled Thermo-hydro-mechanical Modelling of the Full-Scale Emplacement Experiment. Technical Memorandum dated February 2014 (*in preparation*).

Harrington, J.F. and S.T. Horseman. 2003. Gas migration in KBS-3 buffer bentonite: sensitivity of test parameters to experimental boundary conditions. Swedish Nuclear Fuel and Waste Management Co Technical Report SKB TR-03-02. Stockholm, Sweden.

Hobbs, M.Y., P. Gierszewski, A. D'Andrea, F. Garisto, M.R. Jensen, T.F. Kempe, P. Maak, S.B. Russell, G.R. Simmons, A. Vorauer and K. Wei. 2005. Deep Geologic Repository Technology Program - Annual Report 2004. Ontario Power Generation, Nuclear Waste Management Division Report 06819-REP-01200-10146-R00. Toronto, Canada.

Hobbs, M.Y., P. Gierszewski, M.R. Jensen, F. Garisto, T.F. Kempe, T. Lam, P. Maak, G.R. Simmons, A. Vorauer and K. Wei. 2006. Deep Geologic Repository Technology Program - Annual Report 2005. Ontario Power Generation, Nuclear Waste Management Division Report 06819-REP-01200-10155-R00. Toronto, Canada.

Kennell, L., K. Birch, R. Crowe, D. Doyle, J. Freire-Canosa, M. Garamszeghy, F. Garisto, M. Gobien, S. Hirschorn, N. Hunt, P. Keech, E. Kremer, T. Lam, H. Leung, J. McKelvie, C. Medri, A. Murchison, A. Parmenter, U. Stahmer, E. Sykes, J. Villagran, A. Vorauer, T. Wanne and T. Yang. 2012. Technical Program for the Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2011. Nuclear Waste Management Organization Report NWMO TR-2012-01. Toronto, Canada.

Kremer, E., M. Ben Belfadhel, K. Birch, J. Freire-Canosa, F. Garisto, P. Gierszewski, M. Gobien, S. Hirschorn, A. Khan, G. Kwong, T. Lam, H. Leung, P. Lum, P. Maak, S. Russell, K. Sedor, E. Sykes and A. Vorauer. 2009. Technical research and development program for long-term management of Canada's used nuclear fuel – Annual report 2008. Nuclear Waste Management Organization Report NWMO TR-2009-01. Toronto, Canada.

Lemire, R.J., U. Berner, C. Musikas, D.A. Palmer, P. Taylor and O. Tochiyama. 2013. Vol. 13a. Chemical Thermodynamics of Iron, Part I. OECD Nuclear Energy Agency Data Bank (Eds.), OECD Publications. Paris, France.

Loomer, D., Y. Xiang and T. Al. 2013a. Investigations of Methods for Quantifying Diffusive Transport Processes in Sedimentary Rock. Nuclear Waste Management Organization Technical Report NWMO TR-2013-18. Toronto, Canada.

Loomer, D.B., L. Scott, T.A. Al, K.U. Mayer and S. Bea. 2013b. Diffusion-reaction studies in low permeability shale using X-ray radiography with cesium. Applied Geochemistry 39, 49-58.

Mazurek, M., T. Oyama, F. Eichinger and A. de Haller. 2013. Squeezing of Porewater from Core Samples of DGR Boreholes: Feasibility Study. Nuclear Waste Management Organization Technical Report NWMO TR-2013-19. Toronto, Canada.

McKelvie, J., M. Ben Belfadhel, K. Birch, J. Freire-Canosa, M. Garamszeghy, F. Garisto, P. Gierszewski, M. Gobien, S. Hirschorn, N. Hunt, A. Khan, E. Kremer, G. Kwong, T. Lam, H. Leung, P. Maak, C. Medri, A. Murchison, S. Russell, M. Sanchez-Rico Castejon, U. Stahmer, E. Sykes, A. Urrutia-Bustos, J. Villagran, A. Vorauer, T. Wanne and T. Yang. 2010. Technical Program for Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2009. Nuclear Waste Management Organization Report NWMO TR-2010-01. Toronto, Canada.

McKelvie, J., K. Birch, J. Freire-Canosa, M. Garamszeghy, F. Garisto, P. Gierszewski, M. Gobien, S. Hirschorn, N. Hunt, M. Jensen, A. Khan, E. Kremer, G. Kwong, T. Lam, L. Lang, C. Medri, A. Murchison, S. Russell, U. Stahmer, E. Sykes, J. Villagran, A. Vorauer, T. Wanne and T. Yang. 2011. Technical Program for Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2010. Nuclear Waste Management Organization Report NWMO TR-2011-02. Toronto, Canada.

Mobbs, S., G. Shaw, S. Norris, L. Marang, T. Sumerling, A. Albrecht, S. Xu, M. Thorne, L. Limer, K. Smith and G. Smith. 2013. Intercomparison of Models of 14C in the Biosphere for Solid Radioactive Waste Disposal. Radiocarbon Journal 55(2-3).

Mompeán, F.J and H. Wanner. 2003. The OECD Nuclear Energy Agency thermodynamic database project. Radiochimica Acta, 91, 616-622.

Normani, S. D., Y.-J Park, J.F. Sykes and E.A. Sudicky. 2007. Sub-regional modelling case study 2005-2006 status report. Nuclear Waste Management Organization Technical Report NWMO TR-2007-07. Toronto, Canada.

NWMO. 2005. Choosing a way forward: the future management of Canada's used nuclear fuel. Nuclear Waste Management Organization Report APM-REF-00680-23833. Toronto, Canada.

NWMO. 2010. Moving Forward Together: Process for Selecting a Site for Canada's Deep Geological Repository for Used Nuclear Fuel. Nuclear Waste Management Organization Report APM-CORR-06140-23798. Toronto, Canada.

NWMO. 2012a. Used Fuel Repository Conceptual Design and Postclosure Safety Assessment in Crystalline Rock (Pre project Report). Nuclear Waste Management Organization Report NWMO TR-2012-16. Toronto, Canada.

NWMO. 2012b. SYVAC3-CC4 Theory, Version SCC409. Nuclear Waste Management Organization Technical Report, NWMO TR-2012-22. Toronto, Canada.

NWMO. 2013. Postclosure Safety Assessment of a Used Fuel Repository in Sedimentary Rock, Pre-Project Report. Nuclear Waste Management Organization Report NWMO TR-2013-07. Toronto, Canada.

Olivella, S., A. Gens, J. Carrera and E.E. Alonso. 1996. Numerical modelling for a simulator (CODE_BRIGHT) for the coupled analysis of saline media. Engineering Computations 13, 87-112

Palleske , C., J. Hutchinson, D. Elmo and M. Diederichs. 2013a. Impacts of limited data collection windows on accurate rockmass simulation using discrete fracture networks. 47th U.S. Rock Mechanics Geomechanics Symp., ARMA. San Francisco, USA.

Palleske, C.K., M. Lato, J. Hutchinson, D. Elmo and M. Diederichs. 2013b. Impacts of limited spacing and persistence data on DFN modelling of rockmasses. Proceedings: Canadian Geotechnical Conference. Montreal, Quebec.

Peltier, W.R. 2002. A Design Basis Glacier Scenario. Ontario Power Generation Report 06819-REP-01200-10069-R00. Toronto, Canada.

Peltier, W.R. 2006. Boundary conditions data sets for spent fuel repository performance assessment. Ontario Power Generation, Nuclear Waste Management Division, Technical Report 06819-REP-01200-10154-R00. Toronto, Canada.

Perras, M.A. and M.S. Diederichs. 2014. Predicting the dimensions of excavation damage zones using continuum mechanics. Submitted for publication.

Perras, M.A., C. Langford, E. Ghazvinian and M.S. Diederichs. 2012. Numerical delineation of the excavation damage zones: From rock properties to statistical distribution of the dimensions. In the Proceedings of Eurock 2012. Stockholm, Sweden.

Perras, M.A. 2014. Understanding and predicting excavation damage in sedimentary rocks: A continuum based approach. PhD Thesis, Queen's University. Kingston, Ontario, Canada.

Priyanto, D.G., C-S. Kim and D.A. Dixon. 2013. Geotechnical Characterization of a Potential Shaft Backfill Material. Nuclear Waste Management Organization Report, NWMO TR-2013-03. Toronto, Canada.

Quintessa and Geofirma. 2011. Postclosure Safety Assessment Data: Geofirma Engineering Ltd. and Quintessa Ltd. Report for the Nuclear Waste Management Organization NWMO DGR-TR-2011-32. Toronto, Canada.

Razdan, M. and D.W. Shoesmith. 2014. Influence of trivalent-dopants on the structural and electrochemical properties of uranium dioxide (UO2). Journal Electrochem. Soc. 161 (3), H105-H113.

Russell, S., F. Garisto, P. Gierszewski, M. Hobbs, M. Jensen, T. Kempe, T. Lam, P. Maak, G. Simmons, A. Vorauer and K. Wei. 2007. Technical research and development program for long-term management of Canada's used nuclear fuel – Annual Report 2006. Ontario Power Generation report 06819-REP-01200-10163-R00. Toronto, Canada.

Selvadurai, A.P.S. and L. Jenner. 2012. Radial flow permeability testing of an argillaceous limestone. Ground water, 1-7.

Selvadurai, A.P.S., A. Letendre and B. Hekimi. 2011. Axial flow hydraulic pulse testing of an argillaceous limestone. Environ Earth Science 64, 2047-2058.

Slater, G.F., D.P. Moser and B. Sherwood Lollar. 2013. Development of Microbial Characterization Techniques for Low-Permeability Sedimentary Rocks. Nuclear Waste Management Organization Technical Report NWMO TR-2013-17.

SNC-Lavalin Nuclear Inc. 2011a. APM Conceptual Design and Cost Estimate Update Deep Geological Repository Design Report Crystalline Rock Environment Copper Used Fuel Container. Nuclear Waste Management Organization Report APM-REP-00440-0001. Toronto, Canada.

SNC-Lavalin Nuclear Inc. 2011b. APM conceptual design and cost estimate update Deep geological repository design report Sedimentary rock environment, Copper Used Fuel Container. Nuclear Waste Management Organization Report APM-REP-00440-0002. Toronto, Canada.

Spiessl, S.M., K.U. Mayer and K.T.B. MacQuarrie. 2009. Reactive Transport Modelling in Fractured Rock-Redox Stability Study. Nuclear Waste Management Organization Technical Report NWMO TR-2009-04. Toronto, Canada.

Srivastava, R.M. 2002a. Probabilistic Discrete Fracture Network Models for the Whiteshell Research Area. Ontario Power Generation Nuclear Waste Management Division Report 06819-REP-01200-10071-R00. Toronto, Canada.

Srivastava, R.M. 2002b. The discrete fracture network model in the local scale flow system for the Third Case Study. Deep Geologic Repository Technology Report 06819-REP-01300-10061-R00. Ontario Power Generation. Toronto, Ontario.

Srivastava, R. M. and P. Frykman. 2006. Fracture Network Modelling: Verification of Procedures and Validation using Lägerdorf Quarry Field Data. Deep Geologic Repository Technology Report 06819-REP-01200-10122-R00. Ontario Power Generation. Toronto, Ontario.

Stroes-Gascoyne, S., A. Schippers, B. Schwyn, S. Poulain, C. Sergeant, M. Simonoff, C. Le Marrec, S. Altmann, T. Nagaoka, L. Mauclaire, J. McKenzie, S. Daumas, A. Vinsot, C. Beaucaire and J.M. Matray. 2007. Microbial community analysis of Opalinus Clay drill core samples from the Mont Terri Underground Research Laboratory, Switzerland. Geomicrobiology Journal 24, 1-17.

Sykes, J.F., S.D. Normani, E.A. Sudicky and R.G. McLaren. 2004. Sub-regional scale groundwater flow within an irregular discretely fractured Canadian Shield setting. Ontario Power Generation, Nuclear Waste Management Division, Technical Report 06819-REP-01300-10061-R00. Toronto, Canada.

Szakálos, P., G. Hultquist, and G. Wikmark. 2007. Corrosion of Copper by Water. Electrochemical and Solid-State Letters 10(11), C63-C67.

Torudd, J. and A.B. Facilia. 2010. Long term radiological effects on plants and animals of a deep geological repository, SR-Site Biosphere. Swedish Nuclear Fuel and Waste Management Co Technical Report SKB TR-10-08. Stockholm, Sweden.

Vilks, P. 2011. Sorption of Selected Radionuclides on Sedimentary Rocks in Saline Conditions – Literature Review. Nuclear Waste Management Organization Technical Report NWMO TR-2011-12. Toronto, Canada.

Vilks, P. and N.H. Miller. 2013. Sorption Studies with Sedimentary Rock under Saline Conditions. Nuclear Waste Management Organization Technical Report NWMO TR-2013-22 (In progress). Toronto, Canada.

Vilks, P., N.H. Miller and K. Felushko. 2011. Sorption Experiments in Brine Solutions with Sedimentary Rock and Bentonite. Nuclear Waste Management Organization Technical Report NWMO TR-2011-11. Toronto, Canada.

Vogt, T. 2013. Full-Scale Emplacement (FE) Experiment Excavation & Instrumentation. Available at http://www.modern-fp7.eu/fileadmin/modernconference/Presentations.

Walton G., M. Lato, H. Anchutz, M.A. Perras and M.S. Diederichs. 2014. Geophysical detection of fractures, fracture zones, and rock damage in a hard rock excavation - experience from the Aspo Hard Rock Laboratory in Sweden. Submitted for publication.

Wilk, L. 2013. CANDU Fuel Burnup and Power Rating 2012 Update. Nuclear Waste Management Organization Technical Report NWMO TR-2013-02. Toronto, Canada.

Wilk, L., and G. Cantello. 2006. Used Fuel Burnups and Power Ratings For OPG Owned Used Fuel. Ontario Power Generation Report 06819-REP-01300-10121-R00. Toronto, Canada.

World Nuclear Transportation Institute. 2013. Annual Review. http://www.wnti.co.uk/media/63073/AR_EN_FEB14_V1.pdf

Wu, L., Y. Beauregard, Z. Qin, S. Rohani and D.W. Shoesmith. 2012. A model of the influence of steel corrosion products on nuclear fuel corrosion under permanent disposal conditions. Corrosion Science 61, 83-91.

Yin, Y., S.D. Normani, J.F. Sykes and M. Barnard. 2013. Preliminary Hydrogeologic Modelling of a Crystalline Rock Setting in Western Greenland. Nuclear Waste Management Organization Technical Report NWMO TR-2013-20 (In progress). Toronto, Canada.

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APPENDIX A: TECHNICAL REPORTS, RESEARCH PAPERS, CONTRACTORS AND AWARDED SCHOLARSHIPS

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Avis, J. and N. Sgro. 2013. Probabilistic Safety Assessment using Detailed Groundwater Flow and Transport Models. Nuclear Waste Management Organization Technical Report NWMO TR-2013-09. Toronto, Canada.

Crowe, R., K. Birch, J. Chen, D. Doyle, F. Garisto, M. Gobien, N. Hunt, S. Hirschorn, M. Hobbs, P. Keech, L. Kennell, E. Kremer, P. Maak, J. McKelvie, C. Medri, M. Mielcarek, A. Murchison, A. Parmenter, R. Ross, E. Sykes and T. Yang. 2013. Technical Program for Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2012. Nuclear Waste Management Organization Report NWMO TR 2013-01. Toronto, Canada.

Davis, D. 2013. Application of U-Pb Geochronology Methods to the Absolute Age Determination of Vein Calcite. Nuclear Waste Management Organization Technical Report NWMO TR-2013-21 (In progress). Toronto, Canada.

Eichinger, F. and H.N. Waber. 2013. Matrix Porewater in Crystalline Rocks: Extraction and Analysis. Nuclear Waste Management Organization Technical Report, NWMO TR-2013-23. Toronto, Canada.

Garisto F. and M. Gobien. 2013. SYVAC3-CC4 Verification and Validation Summary. Nuclear Waste Management Organization Technical Report NWMO TR-2013-14. Toronto, Canada.

Garisto, F. 2013. Fifth Case Study: Features, Events and Processes. Nuclear Waste Management Organization Technical Report NWMO TR-2013-06. Toronto, Canada.

Gobien, M., F. Garisto, and E. Kremer. 2013. Fifth Case Study: Reference Data and Codes. Nuclear Waste Management Organization Technical Report NWMO TR-2013-05 (In progress). Toronto, Canada.

Loomer, D., Y. Xiang and T. Al. 2013. Investigations of Methods for Quantifying Diffusive Transport Processes in Sedimentary Rock. Nuclear Waste Management Organization Technical Report NWMO TR-2013-18. Toronto, Canada.

Mazurek, M., T. Oyama, F. Eichinger and A. de Haller. 2013. Squeezing of Porewater from Core Samples of DGR Boreholes: Feasibility Study. Nuclear Waste Management Organization Technical Report, NWMO TR-2013-19. Toronto, Canada.

NWMO. 2013. Postclosure Safety Assessment of a Used Fuel Repository in Sedimentary Rock, Pre-Project Report. Nuclear Waste Management Organization Report NWMO TR-2013-07. Toronto, Canada.

Priyanto, D. G., C. S. Kim and D.A. Dixon. 2013. Geotechnical Characterization of a Potential Shaft Backfill Material. Nuclear Waste Management Organization Technical Report NWMO TR-2013-03. Toronto, Canada.

Slater, G.F., D.P. Moser and B. Sherwood Lollar. 2013. Development of Microbial Characterization Techniques for Low-Permeability Sedimentary Rock. Nuclear Waste Management Organization Technical Report, NWMO-TR-2013-17. Toronto, Canada.

Vilks, P. and N.H. Miller. 2013. Sorption Studies with Sedimentary Rock Under Saline Conditions. Nuclear Waste Management Organization Technical Report NWMO TR-2013-22 (In Progress). Toronto, Canada.

Wilk, L. 2013. CANDU Fuel Burnup and Power Rating 2012 Update. Nuclear Waste Management Organization Technical Report NWMO TR-2013-02. Toronto, Canada.

Yin, Y., S.D. Normani, J.F. Sykes and M. Barnard. 2013. Preliminary Hydrogeologic Modelling of a Crystalline Rock Setting in Western Greenland. Nuclear Waste Management Organization Technical Report NWMO TR-2013-20 (In Progress). Toronto, Canada.

A.2 Refereed Journal Publications, Conference Presentations, Invited Presentations and Conference Sessions Chaired

Calder N., R. Walsh and J. Avis. 2013. 3D Gas Transport Model of LASGIT Gas Injection Tests. FORGE Symposium 2013, February 5-7, Luxembourg.

Calder N., R. Walsh and J. Avis. 2013. FORGE Repository Scale Benchmark Modelling Using T2GGM. FORGE Symposium 2013, February 5-7, Luxembourg.

Clark, I.D., T.A. Al, M. Jensen, L. Kennell, M. Mazurek, and R. Mohapatra. 2013. Paleozoic Brines Preserved in an Ordovician Aquiclude. Geology 41(9), 951–954.

Garisto, F. (NWMO). International High Level Radioactive Waste Management (IHLRWM) Conference, April 28 – May 2, 2013. Session: Engineered Systems for Disposal.

Garisto, F., J. Avis, M. Gobien, C. Medri and E. Kremer. 2013. Fourth Case Study: Analysis of Disruptive Scenarios. International High Level Radioactive Waste Management (IHLRWM) Conference. Albuquerque, USA.

Gobien, M. and F. Garisto. 2013. Modelling Container Failure in a Deep Geologic Repository. International High Level Radioactive Waste Management (IHLRWM) Conference. Albuquerque, USA.

He, H., M.Razdan, L.Wu and D.W.Shoesmith; The Influence of Fission Product Doping and Non-Stoichiometry on the Electrochemical Reactivity of Uranium Dioxide; Zing Electrochemistry Conference, Lanzarote, Canary Islands, Spain; February 26 (2013) (PLENARY LECTURE).

Hill S.L.W., and D.W.Shoesmith, Carbon Steel Corrosion in Simulated Groundwater Solutions Containing Low Concentrations of Hydrogen Peroxide, Centre for Advanced Materials and Biomaterials Research Meeting, Western University, London, ON, November 1 (2013) (Poster).

Hill, S.L.W., and D.W.Shoesmith., Corrosion of Grade70 A516 Carbon Steel in High Chloride Environments under Nuclear Waste Disposal Conditions, Surface Canada 2013, Western University, London, ON, May 8 (2013) (Poster).

Hunt, N.G., P. Gierszewski, E. Kremer and S. Russell. 2013. Used Fuel Repository Postclosure Safety Assessment in Crystalline Rock. 2nd International Safety Case Symposium, The Safety Case for Deep Geological Disposal of Radioactive Waste: 2013 State of the Art. Paris, France.

Jakupi, P., I.Barker, S.Ramamurthy, R.Jacklin, D.W.Shoesmith, D.Moser and P.Keech, Microstructural Characterization and Strain Analysis of Cold-sprayed and Electrodeposited Copper Coatings on Steel using Electron Backscatter Diffraction, Materials Science and Technology 2013, Montreal, QC, October 27-31 (2013).

Jakupi, P., I.Barker, S.Ramamurthy, R.Jacklin, D.W.Shoesmith, D.Moser and P.Keech, Applications of the Electron Back-scatter Diffraction (EBSD) Technique to Industrial Alloys and Coatings, Surface Canada 2013, Western University, London, ON, May 9 (2013).

Kozak, M. (Intera Inc.), E.P. Kremer, (NWMO). International High Level Radioactive Waste Management (IHLRWM) Conference, April 28 – May 2, 2013. Session: Total Repository System, Session 2.

Kremer, E.P. (NWMO), P. Swift, (Sandia National Laboratories). International High Level Radioactive Waste Management (IHLRWM) Conference, April 28 – May 2, 2013. Session: Total Repository System, Session 4.

Kremer, E.P. (NWMO). International High Level Radioactive Waste Management (IHLRWM) Conference, April 28 – May 2, 2013. Session: Natural Systems for Disposal.

Kremer, E.P., N.G. Hunt, J.D. Avis, T. Chshyolkova, F. Garisto, P. Gierszewski, M. Gobien, C.I. Kitson, C.L.D. Medri, T.W. Melnyk and L.C. Wojciechowski. 2013. Fourth Case Study: Postclosure Safety Assessment of a Used Fuel Repository in Crystalline Rock. International High Level Radioactive Waste Management (IHLRWM) Conference. Albuquerque, USA.

Liu, N., M.Razdan and D.W.Shoesmith, Electrochemical Study of Doped UO_2 in Slightly Alkaline Sodium Carbonate/Bicarbonate Solutions, Centre for Advanced Materials and Biomaterials Research Meeting, Western University, London, ON, November 1 (2013) (Poster).

Partovi-Nia, R., J.Chen, D.Zagidulin, S.Ramamurthy and D.W.Shoesmith, Corrosion of Cold-spray Deposited Copper Coatings on Steel Substrates, 223rd Electrochemical Society Meeting, Toronto, ON, May 12-17 (2013).

Partovi-Nia, R., S.Ramamurthy, D,Zagidulin, J.Chen, B.Jacklin and D.W.Shoesmith; Corrosion of Cold-Spray Copper Deposits on Steel Substrates, Research in Progress Symposium, CORROSION 2013, Orlando, FL, USA, march 17-21 (2013).

Partovi-Nia, R., Z.Qin, D.Zagidulin, J.J.Noel and D.W.Shoesmith, Electrochemical Study of Copper Corrosion under Anoxic Conditions, Surface Canada 2013, May 8 (2013) (Poster).

Qin, Z., W-J.Cheong, P.G.Keech, J.C.Wren and D.W.Shoesmith, Modelling the Development of Locally Acidified Sites within Corroding Nuclear Fuel, Fifth International Workshop on Long-term Prediction of Corrosion Damage in Nuclear Waste Systems, Asahikawa, Japan, October 6-10 (2013).

Qin, Z., W.J.Cheong, P.G.Keech, J.C.Wren and D.W.Shoesmith, Modelling the Development of Locally Acidified Sites within Corroding Nuclear Fuel, Centre for Advanced Materials and Biomaterials Research Meeting, Western University, London, ON, November 1 (2013) (Poster).

Ramamurthy, S., D.Zagidulin, J.Chen, P.Jakupi, R.Jacklin, P.Keech and D.W.Shoesmith, Electrochemical behaviour of Copper-coated Carbon Steel, Electrochemical Society Meeting, San Francisco, CA, October 27-31 (2013).

Razdan M., and D.W.Shoesmith; The Electrochemistry of Uranium Dioxide in Acidic Hydrogen Peroxide Solutions, Mater.Res.Soc.Symp.Proc.Vol. 1475, 299-304 (2012).

Razdan, M., J.J.Noel and D.W.Shoesmith, The Composition of Oxide Films on Gd-doped Uranium Dioxide, Electrochemical Society Meeting, San Francisco, CA, October 27-31 (2013).

Razdan, M., and D.W.Shoesmith, The Influence of pH and Carbonate Concentration on the Electrochemical Reactivity of Gd-doped Uranium Dioxide, Surface Canada 2013, Western University, London, ON, May 9 (2013) (Poster).

Razdan, M. and D.W. Shoesmith. 2012. The Electrochemistry of Uranium Dioxide in Acidic Hydrogen Peroxide Solutions, Mater.Res.Soc.Symp.Proc.Vol. 1475, 299-304.

Saso, J.K., R. Caldas, L. W. Diamond, A. Parmenter and T. A. Al. 2013. Investigation of ancient fluid migration in Ordovician carbonates in the Michigan Basin using secondary minerals, Goldschmidt Conference, Florence, Italy, August 25-30, 2013 (Poster).

Shoesmith, D.W., The Chemistry of Spent Nuclear Fuel Inside a Failed Nuclear Waste Container, Faculty of Science, University of Ontario Institute of Technology, Oshawa, November 21 (2013) (INVITED).

Shoesmith, D.W., The Design and Corrosion Performance of High Level Nuclear Waste Containers, Materials Science and Technology 2013, Montreal, QC, October 27-31 (2013) (INVITED).

Shoesmith, D.W., The Nuclear Future: Can We Make it Safe? Memorial University, St. John's, Newfoundland, April 25 (2013) (ELIZABETH LAIRD MEMORIAL LECTURE).

Shoesmith, D.W., The Physical and Chemical Characterization of Corroded Surfaces, Faculty of Science, Memorial University, St. Johns, April 26 (2013) (INVITED).

Shoesmith, D.W., The Properties of Spent Nuclear Fuel under Waste Disposal Conditions, Materials Science and Technology 2013, Montreal, QC, October 27-31 (INVITED).

Shoesmith, D.W., The Spectroscopic and Microscopic Characterization of Electrochemically Reactive (Corroding) Surfaces, Department of Chemistry, University of British Columbia, Vancouver, BC, November 13 (2013) (INVITED).

Shoesmith, D.W., Waste Forms for Actinides, Mineralogical Association of Canada Short Course on Uranium, Winnipeg, MB, May 20-21 (2013) (INVITED).

Shoesmith, D.W. 2013. The chemistry/electrochemistry of spent nuclear fuel as a waste form. In "Uranium, Cradle to Grave", edited by P. Burns and G. Sigmon. Mineralogical Society of Canada, Short Course Series Vol. 43, 337-368.

Walsh R., N. Calder and J. Avis. 2013. 3D Water and Gas Transport Model of the HG-A Experiment. FORGE Symposium 2013, February 5-7, Luxembourg.

Wu, L., and D.W.Shoesmith, The Role of Fission Products on Spent Nuclear Fuel Corrosion in Hydrogen Peroxide Solutions, Surface Canada 2013, Western University, London, ON, May 8 (2013) (Poster).

Wu, L., Z.Qin and D.W.Shoesmith, The Local Redox Conditions within Spent Nuclear Fuel inside a Failed Waste Container, Electrochemical Society Meeting, San Francisco, CA, October 27-31 (2013).

Wu, L., Z.Qin, D.W.Shoesmith, Modelling the Redox Conditions Inside a Failed Nuclear Waste Container, 223rd Electrochemical Society Meeting, Toronto, ON, May 12-17 (2013).

A.3 SCHOLARSHIPS

NWMO awarded the following students industrial postgraduate scholarships in collaboration with the Natural Sciences and Engineering Research Council (NSERC) of Canada:

Hill, Shannon, NACE International North Eastern Conference. Student Poster Award (1st place). Toronto, October 2012.

Nazhen Liu, Christian. Sievertz Award (2012) (Western).

Razdan, Mayuri. N.Stewart McIntyre Award for Excellence in Surface Analysis, July (2012).

Wu, Linda, MITACS Accelerate Award (with the Nuclear Waste Management Organization, Toronto) (June 2013)

A.4 LIST OF RESEARCH COMPANIES, CONSULTANTS AND UNIVERSITIES

Alberta Innovates-Technology Futures
AMEC NSS Limited
ANRIC Enterprises Inc.
Atomic Energy of Canada Ltd
ATS Automation
Babcock & Wilcox Canada

Canadian Hazards Information Services
Candesco
Conestoga College
EcoMetrix Inc
GeoEco Consulting 2010
Geofirma Engineering Ltd
Golder Associates Ltd
Integran Technologies Inc.
Integrity Corrosion Consulting Ltd.
International Safety Research Inc.
McGill University
MegaStir Technologies Inc.
National Research Council Canada - Industrial Materials Institute (London, Ontario)
Novika Solutions
Royal Military College of Canada
Ryerson University
SENES Consultants Limited
SKB International Consultants
TerraTek (Schlumberger)
University of Bern
University of British Columbia
University of Ottawa
University of Saskatchewan
University of Toronto
University of Virginia
University of Waterloo
University of Western Ontario
University of Windsor
Virginia Polytechnic Institute and State University
Wilfrid Laurier University

APPENDIX B: ABSTRACTS FOR TECHNICAL REPORTS FOR 2013

ABSTRACT

Title: Technical Program for Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2012
Report No.: NWMO TR-2013-01
Author(s): R. Crowe, K. Birch, J. Chen, D. Doyle, F. Garisto, M. Gobien, N. Hunt, S. Hirschorn, M. Hobbs, P. Keech, L. Kennell, E. Kremer, P. Maak, J. McKelvie, C. Medri, M. Mielcarek, A. Murchison, A. Parmenter, R. Ross, E. Sykes and T. Yang
Company: Nuclear Waste Management Organization
Date: September 2013

Abstract
This report is a summary of activities and progress in 2012 for the Nuclear Waste Management Organization's (NWMO's) Technical Program. The primary purpose of the Technical Program is to support the implementation of Adaptive Phased Management (APM), Canada's approach for long-term management of used nuclear fuel. Significant technical program achievements in 2012 are summarized below.

- NWMO continued to participate in international research activities associated with the SKB Äspö Hard Rock Laboratory, the Mont Terri Rock Laboratory, the Greenland Analogue Project, the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency Research Projects, and the international working group on biosphere modelling (BIOPROTA).

- NWMO provided research contracts and research grants to 11 Canadian universities, 3 foreign universities and supported 6 postgraduate scholarships in 2012 as an approved industrial partner with the Natural Science and Engineering Research Council of Canada.

- NWMO's research program published 21 NWMO technical reports and submitted 12 abstracts for presentation at international conferences focused on environmental radioactivity and radioactive waste management.

- NWMO continues to pursue engineering conceptual designs, canister and emplacement designs, cost estimates, transportation logistics and implementation schedules in support of APM. A redesign of Used Fuel Packing Plant systems was initiated in 2012 to assess the impact of a reduced size used fuel container.

- NWMO continued to develop a repository monitoring and retrieval program, and continued to review developments in used fuel reprocessing and alternative waste management technologies. The NWMO continues to conduct research on used fuel container corrosion, as applicable to the potentially high salinity bedrock of Canada. The NWMO has initiated experiments for 2013 that are comparable to the high salinity copper corrosion experiments carried out in Sweden.

- The NWMO geoscience program continued to develop plans and methods for detailed site investigations in both crystalline and sedimentary rock in the fields of: geology, radionuclide transport, microbiology, geomechanics, seismicity, long term geosphere stability and hydrogeology. NWMO continued to develop and sponsor modelling and analytical methods that will be used to assess long-term geosphere performance. New

research programs to develop methodologies for age-dating of minerals within fractures or vein and for the identification of paleoseismic events were initiated.

- NWMO continued to maintain and improve the models and datasets used to support the safety assessment requirements of potential sites and repository designs.

- NWMO concluded work on an illustrative case study investigating the postclosure behaviour of an APM deep geological repository situated at a hypothetical crystalline site. NWMO initiated work in 2012 on an illustrative case study to investigate the postclosure behaviour of an APM deep geological repository situated at a hypothetical sedimentary site

ABSTRACT

Title: CANDU Fuel Burnup and Power Rating 2012 Update
Report No.: NWMO TR-2013-02
Author(s): L. Wilk
Company: AMEC NSS
Date: February 2013

Burnups and maximum experienced powers for fuel bundles that have been discharged from Ontario Power Generation, Bruce Power, Hydro-Quebec, and New Brunswick Power reactors were extracted from all available digital archives. The data were statistically analyzed and plotted as frequency histograms.

ABSTRACT

Title: Review of the NWMO Copper Corrosion Allowance
Report No.: NWMO TR-2013-04
Author(s): J. R. Scully[1] and M. Edwards[2]
Company: [1] University of Virginia
[2] Virginia Polytechnic Institute and State University
Date: May 2013

Within this review, NWMO expectations for uniform, microbially induced, underdeposit, pitting corrosions and stress corrosion cracking of thin copper layers in deep geological repositories were examined. The focus was on issues that might call into question or alter the NWMO corrosion allowance depth of 1.27 mm in approximately 1 million years, a value that has been found to be appropriate within this review given current knowledge. This summary highlights the main findings from a critical review of both NWMO documentation and the broader literature.

Current experimental evidence for spontaneous copper corrosion in O2 free waters has not been corroborated by multiple investigators and there is also a lack of agreement regarding equilibrium hydrogen partial pressures for copper corrosion [Cu ⇄ Cu(I) + e-] in DGR environments without oxygen. Although this issue is not completely resolved, there are compelling reasons to accept that these uncertainties should not affect the corrosion allowance because even after considering reasonable expectations for equilibrium Cu(I) and hydrogen partial pressures in the available data, spontaneous corrosion should essentially cease after a short period of time due to establishment of equilibrium H2 partial pressures and mass transport limitations in the thick bentonite layer. Additional experiments could confirm thermodynamic (and mass transport) predictions of conditions where spontaneous corrosion processes cease. There is also evidence to support concern for spontaneous copper corrosion in oxygen free situations at high Cl- concentrations, elevated temperature and at low Cu+ levels, and each of these conditions may exist at some point over a Canadian DGR lifetime. These conditions should be further explored to better define if and when spontaneous corrosion occurs, and what mass transport reactions control rates. If slow molecular hydrogen transport controls these rates also then corrosion rates are likely very low. The likely transition from spontaneity to non-spontaneity upon changes in certain parameters could in theory be experimentally confirmed.

Assuming that O2 free uniform corrosion is spontaneous, kinetic models have been developed for formation of CuOH in pure water and Cu2S in sulfide containing environments. These kinetic models for spontaneous uniform corrosion rates rely on strong arguments for mass transport control and low HSlevels supplied by microbial processes. Should these conditions prevail, rates will be kinetically slow and should cease based on thermodynamic arguments. Alternative rate limiting factors have been discussed. Underdeposit corrosion depths appear to have been adequately represented for the short time period when corrosion is dominated by oxygen, but this issue could be further explored for conditions that might tend to produce more permanent anodes, such as that caused by non-uniform sulfide diffusion towards the canister or hydrogen gas diffusion away from the canister. In principle, one stress corrosion cracking (SCC) mechanism involving HS- may be possible under anoxic conditions but mitigating factors such as limited HS- concentrations in bentonite, mass transport limited HS- transport to crack tips, and sequestration of sulfide suggest that it should not be considered in corrosion allowance to date. Taken together, this review concludes that the NWMO Corrosion Allowance of 1.27 mm in approximately 1 million years is appropriate. To complement this finding, research related activities that will build confidence and further explore the validity of key assumptions have been suggested.

ABSTRACT

Title: Fifth Case Study: Reference Data and Codes
Report No.: NWMO TR-2013-05 (In Progress)
Author(s): M. Gobien, F. Garisto, and E. Kremer
Company: Nuclear Waste Management Organization
Date: December 2013

The Fifth Case Study is an illustrative postclosure safety assessment of a conceptual repository for used nuclear fuel located at a hypothetical site at 500 m depth in a sedimentary rock formation. In contrast, the Fourth Case Study was an illustrative postclosure safety assessment of a conceptual repository for nuclear used fuel located at 500 m depth at a hypothetical site in a crystalline rock formation in the Canadian Shield.

Because the host rock is different in the two studies, the Fifth Case Study conceptual repository design differs from that in the Fourth Case Study. The most notable difference is the method of container placement. In the Fourth Case Study containers are placed vertically in boreholes drilled into the placement room floor; whereas, in the Fifth Case study, the in room placement concept is used, with containers placed on compacted bentonite pedestals along the placement room. The spacing of the placement rooms is also narrower in the Fifth Case Study, i.e., 20m rather than 40m.

The main postclosure safety assessment codes used in the Fifth Case Study are:

- FRAC3DVS-OPG v1.3 – for 3D groundwater flow and radionuclide transport;
- RSM v1.1 – a simple screening model used to identify the key radionuclides and chemical elements of concern;
- SYVAC3-CC4 v9.1– the primary safety assessment system model for calculating the impacts of the repository for scenarios in which contaminants reach the biosphere via groundwater;
- HIM v2.0 – for calculating dose consequences for the Inadvertent Human Intrusion Scenario; and
- T2GGM v3.1– for 3D two-phase flow gas transport.

These codes and their datasets are maintained under a software quality assurance system at the NWMO. The codes are described briefly in this report.

The reference datasets used in the Fifth Case Study are based on a combination of the site conceptual model information and the repository design description, with much of the general material properties and other input parameters adopted from the Fourth Case Study, where appropriate. Other data were updated to reflect the expected conditions in the Fifth Case Study repository system, e.g., high salinity groundwater. This report provides a summary of all the data selected, and indicates the references where further details may be found.

ABSTRACT

Title: Fifth Case Study: Features, Events and Processes
Report No.: NWMO TR-2013-06
Author(s): F. Garisto
Company: Nuclear Waste Management Organization
Date: August 2013

Abstract
The Fifth Case Study is a postclosure safety assessment of a deep geologic repository for used CANDU fuel at a hypothetical site in a sedimentary rock environment. It differs from previous Canadian repository safety studies, including the Third and Fourth Case Studies, in that it considers a sedimentary rock environment rather than a crystalline rock environment.

For the purposes of the Fifth Case Study, the repository is assumed to be located at a hypothetical site within the Michigan Basin in Ontario. The geosphere rock mass in the Michigan Basin has low permeability, but a sensitivity case with more permeable rock is also considered. The repository is placed at 500 m depth as a design assumption and the reference container has an outer copper shell for corrosion protection, an inner steel vessel for structural support and a capacity to hold 360 used fuel bundles. The containers are placed in the repository using the in-room placement design.

The safety assessment of a repository must consider a broad range of factors that could potentially affect the behaviour of the repository, contaminants arising from it and its environment over the periods of interest. These factors may be features of the repository or site (e.g., waste type, repository depth), events (e.g., earthquakes, climate change) or processes (e.g., sorption), and are known collectively as FEPs. They are used as input for scenario identification and subsequent conceptual model development for the safety assessment.

However, not all potential FEPs are necessarily included in a given safety assessment. This report, therefore, provides a structured and comprehensive list of possible FEPs relevant to the Fifth Case Study design and site. For each FEP, this report:

- provides a brief description of the FEP;
- discusses its relevance to the Fifth Case Study repository system; and
- identifies the scenarios where relevant FEPs are considered within the conceptual models developed for the Fifth Case Study.

The development of a safety case for a site-specific safety assessment would proceed in stages from conceptual to detailed studies. The Fifth Case Study is a scoping study and is based on a hypothetical repository and site. The present FEPs assessment is representative of the level of information and analysis that would be available during the early stages of siting.

ABSTRACT

Title: Postclosure Safety Assessment of a Used Fuel Repository in Sedimentary Rock, Pre-Project Report
Report No.: NWMO TR-2013-07
Author(s): Nuclear Waste Management Organization
Company: Nuclear Waste Management Organization
Date: December 2013

Abstract
For decades Canadians have been using electricity generated by nuclear power reactors in Ontario, Quebec and New Brunswick. When used nuclear fuel is removed from a reactor, it is considered a waste product, is radioactive and requires careful management. Although its radioactivity decreases with time, chemical toxicity persists and the used fuel will remain a potential health risk for many hundreds of thousands of years. Canada's used nuclear fuel is now safely stored on an interim basis at licensed facilities located where it is produced.

The Nuclear Waste Management Organization (NWMO) is responsible for the implementation of Adaptive Phased Management (APM), the federally-approved plan for safe long-term management of Canada's used nuclear fuel. Under the APM plan, used nuclear fuel will ultimately be placed within a deep geological repository in a suitable rock formation.

The repository and its surroundings comprise a system that is designed to protect people and the environment through multiple barriers. These barriers include the ceramic used fuel, long-lived corrosion resistant containers, engineered sealing materials and the surrounding geosphere.

Safety is a priority for the implementation of the APM program. To support the focus on safety, the NWMO conducts a wide range of complementary activities, including research, design development, technology demonstration and safety assessment, which are necessary to assess the performance of the multi-barrier repository concept at timeframes relevant to illustrating long-term safety.

A site selection process is currently underway to identify a safe site for a deep geological repository in an informed and willing host community. The process of site selection will take several years. As potentially suitable sites are identified with interested communities, detailed field studies and geoscientific site characterization activities will be conducted to assess whether the APM multi-barrier repository concept could be safely implemented to meet rigorous regulatory requirements.

At this very early stage in the process, before specific sites have been identified for detailed examination, it is useful to conduct generic studies to illustrate the long-term performance and safety of the multi-barrier repository system within various geological settings.

This report provides an illustrative case study of the current multi-barrier design and postclosure safety of a deep geological repository in a hypothetical sedimentary setting. The purpose of this case study is to present and illustrate a postclosure safety assessment methodology that demonstrates how Canadian Nuclear Safety Commission (CNSC) expectations are met, as documented in CNSC Guide G-320 on Assessing the Long Term Safety of Radioactive Waste Management. For a licence application for an actual candidate site, a full safety case would be prepared that would include the results of site-specific geoscience investigations, an associated

deep geological repository design and a more comprehensive safety assessment than described in this document.

Geosphere

A hypothetical geosphere was derived, in part, from experience gained in the Canadian Nuclear Fuel Waste Management Program. It was developed for the purpose of this illustrative case study while the NWMO proceeds with the APM siting process and selection of a preferred site in an informed and willing host community. While the hypothetical site represents one example of a possible sedimentary rock setting in southern Ontario, other characteristics are considered in the safety assessment to illustrate an approach to assessing both long-term safety and the functionality of various barrier systems.

The long-term safety and performance of a used fuel repository will rely in part on the geological setting that surrounds the repository. The geosphere will provide a geomechanically, hydrogeologically and geochemically stable environment. Geomechanical stability enables safe excavation and placement of the containers and engineered barrier system, and also, together with hydrogeological and geochemical stability, isolates the containers from a wide range of future human and natural events. A stable geochemical environment supports the container durability and minimizes contaminant mobility. The ability of the geosphere to support these attributes will be dependent on site-specific conditions.

For the purposes of this illustrative assessment, the hypothetical geosphere is divided into three groundwater systems, which are assumed to have the following characteristics:

1. The shallow groundwater system, located between 0 and 215 m below ground surface, is predominately driven by local and sub-regional scale topographic changes. The average travel time for groundwater to recharge, and then subsequently discharge, in the shallow groundwater zone is typically less than 1000 years. The groundwater in the shallow groundwater zone is fresh and oxygen-rich with a low total dissolved solids concentration.
2. The intermediate groundwater system between 215 and 250 m below ground surface is a transition zone from fresh and oxygen-rich to more mineralized and chemically reducing with depth. At the hypothetical site, the shift from oxidizing to reducing conditions occurs within this system. In the intermediate groundwater system, larger domains of low permeability rock tend to decrease mass transport rates.
3. In contrast with the shallow and intermediate groundwater systems, the groundwater in the deep system below 250 m has a higher total dissolved solids concentration and fluid density, and is chemically reducing. The increased fluid density will influence both energy gradients within the groundwater regime and vertical upward movement of groundwater between the shallow/intermediate and deep groundwater zones.

Design Concept

The current conceptual design for sedimentary rock consists of a repository constructed at a depth of approximately 500 m below surface. This depth was arbitrarily selected for illustrative purposes only; at an actual site the repository depth would be selected based on site-specific attributes to enhance passive long-term safety and the presentation of a repository safety case.

The host rock at 500 m at this hypothetical site is assumed to be a massive limestone formation overlain by a thick shale sequence that is suitable for construction and operation of a used fuel repository. The repository contains a network of horizontal tunnel placement rooms for the base case inventory of 4.6 million used fuel bundles encapsulated in about 12,800 long-lived used

fuel containers. The container design consists of a copper outer vessel, or shell, that encloses a steel inner vessel. The outer copper shell provides effective resistance to container corrosion under deep geological conditions, while the inner steel vessel provides strength for the container to withstand expected hydraulic and mechanical loads, including earthquakes and glaciation. The report also describes observations on sedimentary rock considerations in other countries. A notable difference in this case study is with the copper-shell container design as opposed to the steel-only design primarily being considered in other countries. The design will be further refined and optimized for a licence application.

The used fuel container is supported by a highly compacted bentonite pedestal in its assigned position in the placement room. Bentonite pellets, placed by pneumatic methods, are used to fill all the remaining voids in the container placement room. Bentonite is a durable natural material that is expected to maintain its properties over the long term. Bentonite is a type of clay that swells on contact with water, resulting in its natural self-sealing property.

Postclosure Safety Assessment

The primary safety objective for the deep geological repository is the long-term containment and isolation of the used nuclear fuel. The safety of the repository would be based on a combination of the geology, engineered design, careful operations, and quality assurance processes including review and monitoring. Safety assessment provides a quantitative evaluation of the overall performance of the repository system and its impact on human health and on the environment. In this respect, it is able to identify features or processes that contribute to an understanding and confidence in long-term repository safety.

This illustrative case study focuses on long-term or postclosure safety. This is the period after the repository has been filled with used fuel containers, and has been sealed off and closed. Consistent with CNSC Guide G-320, the study identifies scenarios, models and methods for evaluating safety, with which to assess dose consequences and the influence of uncertainties. The results are compared against interim acceptance criteria for protecting persons and the environment.

The assessment does not try to predict the future, but instead examines the consequences for a range of scenarios, from likely to unlikely to “what if”. The likely scenarios are considered under the heading of “Normal Evolution Scenario.”

Normal Evolution Scenario

The normal evolution scenario presented in this report is based on a reasoned extrapolation of the reference case site and repository characteristics over time, consistent with the expectations of CNSC Guide G-320. The report describes why the used fuel copper containers are expected to remain intact over the timeframe of interest. For the purpose of the reference case normal evolution scenario, a small number of containers are assumed to be placed in the repository with undetected defects in the copper shell. Conservatively, these containers are assumed to be positioned within a placement room associated with the shortest travel time through the geosphere to the surface biosphere. The anticipated effects of glaciations on the assessment are also described.

The postclosure safety assessment adopts scientifically informed, physically realistic assumptions for processes and data that are understood and can be justified on the basis of the results of research. Where there are high levels of uncertainty associated with processes and data, conservative assumptions are adopted and documented to allow the impacts of

uncertainties to be bounded. Data from site investigations will further support the assumptions and be incorporated into future safety assessments.

For the reference case safety assessment, the primary contributor to the public dose over the long term from an assumed small number of defective used fuel containers is the instant release fraction of Iodine-129, a long-lived radionuclide in used fuel that is non-sorbing in the geosphere. The calculated maximum dose for the reference case is about 150,000 times lower than the interim dose acceptance criterion of 0.3 mSv per year for the normal evolution scenario and occurs at the modelling cut-off time of 10 million years after closure. This long timeframe is due, in part, to the combined performance of the repository barrier systems and the time required for Iodine-129 to reach the biosphere. The barrier systems include the long-lived containers, the integrity of the engineered sealing systems and the near-field rock surrounding the repository.

The radiological impact on non-human biota is discussed in the report and the assessment concludes that the effects are negligible for the normal evolution scenario.

The report also concludes that contaminant concentrations are below their associated interim acceptance criteria in the assessment for protecting persons and the environment from hazardous substances, such as copper and other elements released from the used fuel and the containers.

Sensitivity Analyses and Bounding Assessments
Recognizing that there are uncertainties associated with the future evolution of a repository, the NWMO has varied a number of important parameters and assumptions, completed bounding assessments and has developed a number of hypothetical “what-if” scenarios to explore the influence of parameter and scenario uncertainty in assessing long-term safety. This approach is consistent with CNSC Guide G-320 on the use of different assessment strategies. Key parameters that could potentially affect long-term safety are varied in sensitivity cases to understand the impact of uncertainties in these parameters:

- An increase in fuel dissolution rate by a factor of 10;
- An increase of contaminant instant release fractions to 10%;
- An increase in rock mass and excavation damage zone hydraulic conductivities by a factor of 10;
- An increase in rock diffusivity by a factor of 10;
- A 158 m overpressure in the Shadow Lake Formation which is located at a depth of approximately 675 m at the hypothetical site;
- An increase in container degradation by increasing the assumed undetected container defect area by a factor of 10; and
- A decrease in geosphere sorption with a coincident increase in radionuclide solubility limits.

Some parameters are also pushed beyond the reasonable range of variations in bounding assessments. In these cases, parameters are completely ignored by setting their values to zero or by removing physical limits for the following:

- An increase in radionuclide solubility in groundwater by ignoring solubility limits;
- A decrease in radionuclide sorption in the geosphere by ignoring sorption; and
- A decrease in radionuclide sorption in the near field by ignoring sorption.

The results from the sensitivity analysis and the bounding assessments conducted as part of this illustrative case study are shown in Figure E1.

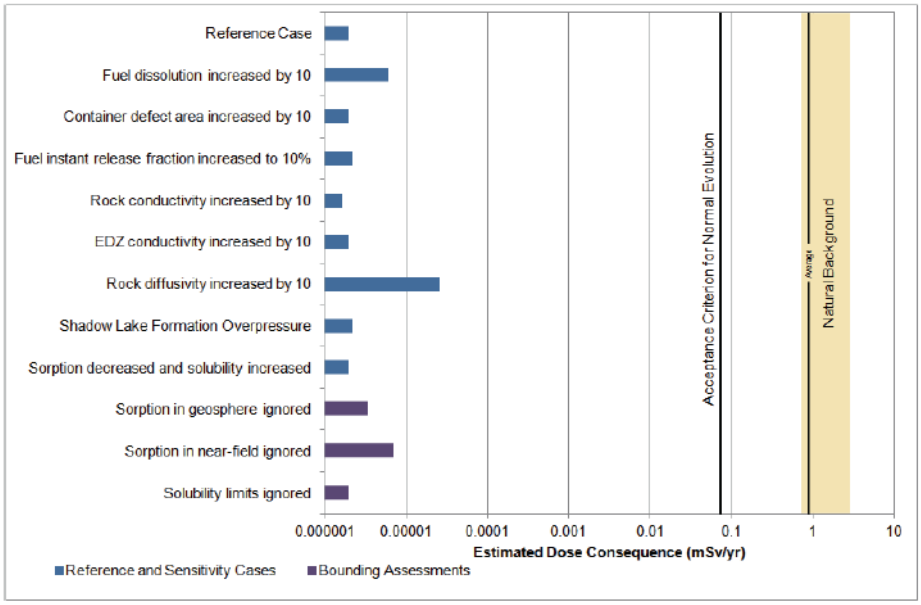

Figure E1: Results from Sensitivity Analysis and Bounding Assessments

The sensitivity analyses show that the impact on dose is small when key parameters are varied. As shown in Figure E1, the parameter with the most significant impact on dose is the rock diffusivity. The dose consequence when the rock diffusivity is increased by a factor of 10 is assessed to be 13 times greater than the reference case value.

The bounding assessments show a small impact on dose when sorption is ignored. When sorption is ignored in the near field, the dose consequence is assessed to be 3.4 times greater than in the reference case. When sorption is ignored in the geosphere, maximum dose is increased to 1.6 times the reference case value and occurs at same time (modelling cut-off time of 10 million years). No impact on dose was observed when radionuclide solubility limits are ignored (see Figure E1).

Recognizing the importance of processes such as used fuel dissolution and sorption as shown in this case study, NWMO maintains active research programs in these areas to continue to improve our understanding of these processes. Nevertheless, even if highly conservative assumptions are adopted where there is uncertainty, the maximum dose rate to a member of the public is still estimated to be orders of magnitude lower than the interim dose acceptance criterion of 0.3 mSv per year.

All the previous results were obtained through deterministic analyses. A further understanding of uncertainties can be obtained through probabilistic modelling. In the present illustrative case study, a probabilistic analysis was conducted on the contaminant release and transport parameters. A total of 120,000 simulations were examined to identify a 95th percentile peak dose rate. The peak dose consequence in this case is assessed to be 37 times greater than for the reference case. This remains 4,000 times below the interim dose acceptance criterion of 0.3 mSv per year.

Disruptive Scenarios
A number of disruptive or “what-if” scenarios are identified by examining possible failure mechanisms. These scenarios are assessed to evaluate the potential impact of major barrier failures on safety, in accordance with CNSC Guide G-320. The disruptive event scenarios considered in this illustrative case study include:

- All containers fail at 60,000 years;
- All containers fail at 10,000 years; and
- Failure of shaft seal.

The container failure scenarios (i.e., all containers fail at 60,000 years and a variation where all containers fail at 10,000 years) indicate a notable increase in the dose results. However, the maximum dose rates remain well below the interim dose acceptance criterion of 1 mSv per year for disruptive scenarios.

The results also reveal that there is low sensitivity of the peak dose rate to the assumed failure time of all used fuel containers in the reference case geosphere. This occurs primarily as the assumed container failure time is longer than the short-lived fission product decay time, meaning that fuel dissolution rates are greatly reduced due to the decay of the gamma and beta radiation fields. Furthermore, the failure times are much smaller than the contaminant transit times to the surface. The remaining actinides and most of the long-lived fission products are delayed principally by diffusion within the natural barrier of the enclosing rock mass so that the peak dose rate, which is dominated by the long-lived and non-sorbing Iodine-129, does not materially change.

The impact of gas generated in the repository is considered for the case where all the containers fail at 10,000 years. The largest potential for gas generation (from the corrosion of steel within the copper container) is examined for this scenario and the model shows that gas could travel upward to the permeable Guelph Formation where it will disperse and dilute laterally underground. However, to provide a bounding estimate, the gas-borne dose consequences are assessed using a set of extremely conservative assumptions to bound the potential dose consequences. A peak dose rate of 0.17 mSv per year is obtained when all the Carbon-14 is assumed to discharge into a house above the repository. This remains a factor of six below the 1 mSv per year interim dose acceptance criterion. For a more realistic case of failure of copper containers over longer times, the dose rates would be substantially lower. For example, if the copper fails on time scales associated with the next glaciation or later, the corresponding dose rates would be well below 0.001 mSv per year due to decay of Carbon-14. The seal failure scenario has shown negligible effect on the predicted dose consequence in this study due to the distance between the containers with undetected defects and the shaft seal.

And finally, a stylized analysis was completed for inadvertent human intrusion. This scenario is a special case, as recognized in CNSC Guide G-320, since it circumvents all engineered and natural repository barriers. The results show that the potential dose to the drill crew, and to a site resident, from early intrusion, that exceeds the dose limit. However, the likelihood of this event occurring is very small due to placing the used fuel containers deep underground in a location with institutional controls in place for a period of time, no economically viable mineral resources, and no potable groundwater resources. Normal deep drilling practices (e.g., control of drilling fluids, use of gamma logging, etc.) will also tend to reduce consequences relative to those estimated here. Although the likelihood of human intrusion cannot be readily defined, it will be very low. The annual risk of health effects from human intrusion is estimated to be less than 1 in 100,000 per year.

Conclusion

This report provides an illustrative postclosure safety assessment of a deep geological repository in a hypothetical sedimentary rock setting. The objective is to provide a partial postclosure safety assessment that shows a structured and systematic approach that is consistent with expectations described in CNSC Guide G-320. The illustrative assessment includes a description of the repository system, systematically identifies scenarios, models and methods for evaluating safety, uses different assessment strategies, addresses uncertainty, and compares the results of the assessment with interim acceptance criteria. It indicates where additional analyses would be undertaken as part of a full safety case for an actual repository site.

The postclosure safety assessment shows, for the normal evolution scenario and associated sensitivity cases, that radiological and non-radiological interim acceptance criteria could be met during the repository's postclosure period.

ABSTRACT

Title: Probabilistic Safety Assessment using Detailed Groundwater Flow and Transport Models
Report No.: NWMO TR-2013-09
Author(s): J. Avis and N> Sgro
Company: Geofirma Engineering Ltd.
Date: April 2013

This work program demonstrates the application of a probabilistic safety assessment (PSA) methodology to computationally intense three-dimensional (3D) numerical simulations of the transport of radionuclides from a hypothetical repository in a fractured granite geosphere. Previous safety assessments conducted by the NWMO have used two modelling approaches: probabilistic safety assessments have been conducted using simplified geosphere and repository transport models, while very detailed deterministic finite-element models have been used to simulate flow and transport for a limited number of cases and a limited number of nuclides. This report describes a proof-of-concept approach to conducting probabilistic simulations using detailed 3D numeric models. Existing numeric models used in the Fourth Case Study (4CS) Assessment (NWMO, 2012) have been simplified and the modelling workflow automated to allow complete simulations to be executed under the control of a probabilistic sampling executive.

The basic scenario includes a water-supply well intersecting a fracture that extends to repository depth. A defective container located within a placement room adjacent to the fracture supplies the radionuclide source-term. A single radionuclide, I-129, is used in the simulations. Parameters describing geosphere, fracture, engineered barrier system (EBS) and placement room excavation
and thermal damage zone (EDZ) are defined in terms of probability distributions, which are sampled under the control of an executive code. Flow and transport simulations are conducted for each realization and model results extracted. Results are analyzed using graphical and regression approaches.

An initial assessment based on transport times indicated by Mean Life Expectancy (MLE) was conducted to validate the 4CS well placement. Subsequently a full transport assessment determined the parameters with the most significant impact on transport related safety assessment metrics. This assessment showed that geosphere properties are the primary controls on radionuclide transport. Additional assessments fixed geosphere variables at median values and focussed on repository components (EBS and EDZ) to determine the relative importance of parameters describing these sub-systems. After proof of concept was demonstrated on a local cluster computer, the assessments were duplicated using cloud based computing resources from Amazon Web Services (AWS). The AWS implementation demonstrates that complex numeric PSA does not require dedicated local hardware and can be conducted using readily available commercial facilities. AWS is also a scalable resource, allowing complex simulations with many thousands of realizations to be conducted, albeit at not insignificant cost.

The approach demonstrated here is ideally suited to the particular attributes of the 4CS geosphere and the single defective container radionuclide transport reference case scenario. However, it could be extended to other scenarios such as multiple container failure and to other models such as TOUGH2.

ABSTRACT

Title: Nuclear Fuel Waste Projections in Canada – 2013 Update
Report No.: NWMO TR-2013-11
Author(s): M. Garamszeghy
Company: Nuclear Waste Management Organization
Date: December 2013

This report updates the 2012 Nuclear Fuel Waste Projections report [Garamszeghy, 2012], summarizes the existing inventory of used nuclear fuel wastes in Canada as of June 30, 2013 and forecasts the potential future arisings from the existing reactor fleet as well as from proposed new-build reactors. The report focuses on power reactors, but also includes prototype, demonstration and research reactor fuel wastes held by AECL which are included in the NWMO mandate.

As of June 30, 2013, a total of approximately 2.42 million used CANDU fuel bundles (approx 48,000 tonnes of heavy metal (t-HM)) were in storage at the reactor sites, an increase of approximately 76,000 bundles from the 2012 report. For the existing reactor fleet, the total projected number of used fuel bundles produced to end of life of the reactors ranges from about 3.4 to 5.2 million used CANDU fuel bundles (69,000 t-HM to 104,000 t-HM), depending upon decisions to refurbish current reactors. The lower end is based on an average of 25 effective full power years (EFPY) of operation for each reactor (i.e. no refurbishment), while the upper end assumes that most reactors are refurbished and life extended for an additional 25 EFPY of operation. This represents a slight increase in the low scenario forecasts from the 2012 report due to the refurbishment and re-start of Bruce A1, Bruce A2 and Point Lepreau. Based on currently announced refurbishment and life extension plans for the existing nuclear reactor fleet in Canada, the current reference scenario projects a total of 4.4 million bundles. For design and safety assessment purposes, the NWMO has conservatively assumed a reference used fuel inventory of 4.6 million CANDU fuel bundles from the existing reactor fleet. Used fuel produced by potential new-build reactors will depend on the size and type of reactor and number of units deployed. New-build plans are at various stages of development and the decisions about whether to proceed with individual projects, reactor technology and number of units have not yet been made. If all of the units where a formal licence application has already been submitted are eventually constructed (i.e. at Darlington), the total additional quantity of used fuel from these reactors could be up to approximately 1.6 million CANDU fuel bundles (30,000 t-HM), or 10,800 PWR fuel assemblies (5,820 t-HM). This total is unchanged from the 2012 report. When decisions on new nuclear build and reactor refurbishment are made by the nuclear utilities in Canada, any resulting changes in forecasted inventory of nuclear fuel waste will be incorporated into future updates of this report.

ABSTRACT

Title: SYVAC3-CC4 Verification and Validation Summary
Report No.: NWMO TR-2013-14
Author(s): F. Garisto and M. Gobien
Company: Nuclear Waste Management Organization
Date: December 2013

The SYVAC3-CC4 code is the reference Canadian system model for assessing the safety of a deep geological repository for used CANDU fuel. It consists of the SYVAC3 executive code and the CC4 system model. The CC4 system model describes a particular repository concept – used CANDU fuel in long-lived containers surrounded by bentonite clay in a stable host rock environment.

The purpose of this report is to summarize the verification and validation studies that have been carried out on SYVAC3-CC4. Many of these studies are documented in various detailed reports; this document serves as a reference summary report. Since the SYVAC3-CC4 code was developed over many years, portions of the current code were tested in earlier studies. These tests are included in this report where relevant.

Full validation of models for long-term assessment of a deep geological repository is not possible, notably because of the long time periods involved. Most of the validation tests involve comparison either with short-term field and laboratory data, or with other similar but independently developed codes or models. A specific focus of the work has been to provide testing of all the functional elements within the system model. The approach adopted is to view validation as an on-going activity that progressively improves confidence in the code results. Overall, the results summarized in this report indicate that at least partial validation tests have been done for a large number of the models in SYVAC3-CC4. The model results are sufficiently reliable for use in safety assessment of a deep geological repository, where the calculated safety margins are significant. Further tests will extend the range of confidence in the results.

ABSTRACT

Title: Development of Microbial Characterization Techniques for Low-permeability Sedimentary Rocks
Report No.: NWMO TR-2013-17
Author(s): G. Slater[1], and D. Moser[2] B. Sherwood Lollar[3]
Company: [1]McMaster University, [2]Desert Research Institute, [3]University of Toronto,
Date: December 2013

Abstract
The development of techniques for the characterization of potential indigenous microbial communities in low-permeability sedimentary rock was undertaken for six core samples of shale, interbedded shale and limestone, argillaceous dolostone and argillaceous limestone using phospholipid fatty acid (PLFA), molecular genetic and traditional microbiological approaches. To circumvent intrinsic properties of these cores (e.g., low biomass and high salinity/clay content), extensive methods development and control comparisons were undertaken. To characterise likely sources of contamination, samples of drilling water were collected and analyzed concurrently with each core segment. In addition, outer surfaces of collected cores were analyzed for PLFA and DNA and the results compared to those from drilling water and core interiors. Pristine subsamples from core interiors were collected by splitting off a minimum of 5 mm of outer core surfaces using a hydraulic splitter and pulverizing interior samples under sterile conditions. Flow cytometry, microscopy and cultivation, as well as PLFA and DNA analysis, resulted in negligible detection of microorganisms in the drilling water. It is hypothesised that the high salinity (1100 kg/m^3) of this water may have lysed most microbial cells originally present in the Lake Huron freshwater from which the drilling fluid was prepared, resulting in near-aseptic drilling.

PLFA were quantified in all core interior samples, corresponding to cell densities of ~1 – 3 x 10^5 cells/gram of rock, approximately an order of magnitude above the calculated detection limit for PLFA analysis of 3 x 10^4 cells/gram of rock. These cell abundances are consistent with the lowest abundances reported for oligotrophic systems, with the exception of some recent reports from oligotrophic marine sediments. PLFA concentrations for estimated rock volumes sampled during surface rinses were comparable to those observed for core interiors, with two exceptions that were one and two orders of magnitude higher. PLFA distributions for core interior and outer rinse samples were unique for all samples analyzed, indicating distinct sources for the depths sampled as well as for outer rinses as compared to core interiors. Likewise, unique distributions of organic molecules present as alkanes and/or unresolved complex mixtures in each core indicate distinction between samples from different lithologies. Conversely, unlike the case of PLFA analysis, Amplified DNA based surveys (16S rRNA gene) failed to detect evidence for indigenous microorganisms in any of the drilling water or core samples. These samples either contained microbial DNA at below detection limits (or were free of it entirely), or, alternatively, possess some feature that degrades or binds free DNA, thereby preventing its detection. After employing optimised DNA extraction and aggressive PCR amplification protocols (e.g. high numbers of PCR cycles, nested PCR in some cases, or use of highly degenerate primers in pyrotag analysis), traces of amplified bacterial DNA were detected from all samples, including the controls. Exhaustive comparisons of 454 pyrotag and traditional clone library results revealed that this DNA was likely derived from low-level reagent contamination. Such amplification of trace level reagent/process contaminants is expected to be an ongoing challenge that must be addressed during the analysis of low biomass rocks. Inhibition of DNA recovery was also observed in these samples as detection limit calibrations utilizing added bacterial cells indicated that DNA could only be recovered from samples containing 4 x 10^5

cells/gram or higher. The cause of this inhibition was not discernible. It may be that strong sorption of DNA to clay particles or the presence of organic compounds inhibiting DNA amplification in our assays were the cause of the poor detection limits.

Overall, the results observed in this sample set indicate that these low-porosity rocks contain, at most, very low levels of biomass, comparable to cell densities observed in oligotrophic marine sediments. However, there are two caveats that must be recognized. First, the poorer detection limits observed for DNA-based methods as compared to the PLFA results means that the two methods cannot be directly compared in this current study. Further optimization of DNA extraction and purification protocols may overcome this limitation. Secondly, the PLFA-based estimates of cell numbers are based on turnover rates developed in experimental studies of surface and shallow subsurface systems. PLFA turnover rates specific to these low biomass, high salinity, low porosity deep subsurface environments have yet to be determined. If PLFA turnover rates are significantly lower in these systems, the estimated cell densities would be an overestimate of viable cells present. Beyond addressing this specific sample set, the experimental and analytical approach developed for this study represents an effective means to assess low biomass systems and should assist in the development of future site investigation plans to detect and characterize life in low-permeability, low biomass environments under consideration for the development of a deep geological repository.

ABSTRACT

Title: Investigations of Methods for Quantifying Diffusive Transport Processes in Sedimentary Rock
Report No.: NWMO TR-2013-18
Author(s): D. Loomer, Y. Xiang and T. Al
Company: University of New Brunswick
Date: December 2013

Abstract
Diffusion measurement techniques for low-permeability sedimentary rocks have been advanced using new and/or modified methods in several areas: i) effective diffusion coefficient (D_e) measurements with confining pressure (CP); ii) improvements in the X-ray radiography (RAD) method; iii) method development for creating partial gas/brine saturation conditions in rock for diffusion studies; and iv) imaging diffusion pathways using scanning electron microscopy (SEM).

The through-diffusion method was modified to measure D_e values normal to bedding before and after confining pressure was applied to the rock sample. As pressure increased from ambient laboratory pressure (AP) to a CP of 12.0 MPa, a 14% decrease in the D_e of tritiated water (D_{eHTO}), and a 17% decrease in the D_e of iodide (D_{eI}) were observed in Queenston Formation shale drill core from the Michigan Basin. The decreases in D_e were much larger for Georgian Bay Formation shale samples (CP of 15.1 MPa): 32% in D_{eHTO} and 44% in D_{eI}. For Cobourg Formation limestone and argillaceous limestone samples (CP of 17.4 MPa), the decrease in D_e for both tracers ranged from 31% to 35%.

The RAD calibration method was revised to use natural sandstones as the calibration matrix for quantifying the correlation between the change in X-ray attenuation and the I^- tracer concentration in a sample. The natural sandstones were not suitable calibration matrices for the non-conservative tracer cesium (Cs^+). As an alternative, the relationships between the calibration functions for the glass vials, sandstones and ceramics observed in the I^- calibration were exploited and a new calibration function for Cs^+ was determined. The revised calibration approach will be used in any future X-ray radiography work.

The D_{eI} and I^--accessible porosity values measured in Opalinus Clay samples from the Mont Terri Underground Rock Laboratory, Switzerland using the RAD method under unconfined conditions were found to be higher than published values. This resulted from the swelling of the Opalinus Clay in the RAD cell. The RAD cell was then re-designed to hold swelling samples. The one D_{eI} value (4.7 x10^{-12} m^2/s) measured using the RAD confining cell is consistent with published values. For cesium (Cs^+) diffusion measurements, the multicomponent reactive transport code MIN3P was used to calculate the Cs^+ concentration profiles. Estimates of the pore diffusion coefficients (D_{pCs}) and the selectivity coefficients (log $K_{Cs+/Na+}$) were obtained using the model-independent parameter estimation code, PEST. The average D_{pCs} parallel to bedding was 1.7 x10^{-9} m^2/s and the average D_{pCs} normal to bedding was 8.1 x10^{-10} m^2/s. The range of measured log $K_{Cs+/Na+}$ values (1.4 to 2.1) is consistent with published values. The log $K_{Cs+/Na+}$ decreases as the Cs^+ tracer concentration increases.

A new method to create and to control gas/brine partial saturation conditions in rock samples is under development. Preliminary studies by the X-ray RAD method show promise. Further development on a new Am-241 gamma ray radiography technique is underway.

Diffusive pathways in the Michigan Basin rock samples were visualized using SEM. The I^- tracer was fixed in rock pores by precipitating insoluble silver iodide, AgI. At the micrometer (μm) scale, characteristic pathways were differentiated.

ABSTRACT

Title: Squeezing of Porewater from Core Samples of DGR Boreholes: Feasibility Study
Report No.: NWMO TR-2013-19
Author(s): M. Mazurek, T. Oyama, F. Eichinger and A. de Haller
Company: University of Bern
Date: November 2013

Abstract
Three archived core samples from boreholes DGR-4, DGR-5 and DGR-6 from the Salina F Unit, Queenston Formation and the Georgian Bay Formation were subjected to squeezing tests at pressures of up to 500 MPa. Two samples did not yield any water, while a total of 0.88 g pore water was obtained from a clay-rich sample from the Blue Mountain Formation (water content = 2.8 wt.%, porosity = 8 %). This water mass was sufficient for a full chemical and water-isotope analysis – the first direct determination of porewater composition in rocks from the DGR boreholes. The results are generally in reasonable agreement with those of independent methods, or the observed differences can be explained. Ancillary investigations included the determination of water content, densities and mineralogy, aqueous extraction of squeezed cores, and SEM investigations to characterise the microtexture of unsqueezed and squeezed rock materials.

It is concluded that squeezing is a promising method of porewater extraction and characterisation and is recommended as a complementary method for future studies. Selection criteria for potentially squeezable samples include high clay-mineral content (correlating to high water content) and low carbonate content (low stiffness, limited cementation). Potential artefacts of the method, such as ion filtration or pressure solution, should be explored and quantified in future efforts.

ABSTRACT

Title: Preliminary Hydrogeologic Modelling of a Crystalline Rock Setting in Western Greenland
Report No.: NWMO TR-2013-20 (In Progress)
Author(s): Y. Yin, S.D. Normani, J.F. Sykes and M. Barnard
Company: University of Waterloo
Date: December 2013

Abstract
A multilateral research project, named the Greenland Analogue Project (GAP), has been initiated for a study site near Russell Glacier, east of Kangerlussuaq in Greenland. The objective of the GAP is to study a natural ice-sheet analogue to enhance current understanding of how future glacial cycles influence the long-term performance of deep geologic repositories. The groundwater modelling developed as a part of this study was undertaken in two separate phases.

This report documents preliminary groundwater modelling. This preliminary illustrative study develops a geologic conceptual model for the study site and regional-scale numerical groundwater models that illustrate the influence of alternate conceptual models, parameters and scenario uncertainty on the subsurface groundwater system and various performance measures. The impact of glacial advances and retreats, and the distribution of permafrost will be investigated in the next phase of research.

Parameter perturbation and scenarios analyses of the base-case hydrogeological modelling study are described, including: 1) alternate total dissolved solids (TDS) vs. fluid density relationships; 2) alternate TDS vs. depth relationships for the rock matrix; 3) permeability vs. depth relationships for deformation zones, including the absence of deformation zones; 4) variations in surface hydraulic boundary conditions; 5) variations in permafrost characterization both in front of and beneath the ice-sheet; and 6) ice-sheet induced hydromechanical coupling through variations in the rate of glacial melting. These scenarios are used to investigate their influence on the subsurface groundwater system and on various performance measures which include freshwater and environmental heads, porewater velocity magnitudes, TDS distributions, and mean life expectancy (MLE). MLE is more appropriate for groundwater systems typified by low rates of mass transport than particle tracking.

The direction of groundwater movement in the shallow zone is heavily influenced by mechanical loading of the ice-sheet and by topography. Except for the higher permeability deformation zones, rates of mass transport are very low in the deep groundwater zone due to very low pore fluid velocity magnitudes. High deformation zone permeabilities, particularly at depth, lead to the greatest depth of surface water migration within the groundwater system. The greatest TDS concentration and MLE value reductions are associated with higher deformation zone permeabilities. MLEs in the deep groundwater zone are insensitive to different characterizations of surface boundary conditions and TDS profiles except for regions at or near deformation zones.

Unlike freshwater heads, environmental heads are not sensitive to variations in TDS profiles, due to the removal of density effects by subtracting from the freshwater heads the excess heads imposed by a pore fluid density greater than that of freshwater. The impact of deglaciation on the groundwater system was investigated in paleohydrogeologic scenarios wherein model

results indicate that deglaciation leads to upward hydraulic gradients and upward TDS migration.

ABSTRACT

Title: Application of U-Pb Geochronology Methods to Absolute Age Determination of Vein Calcite
Report No.: NWMO TR-2013-21 (In Progress)
Author(s): D. Davis
Company: University of Toronto
Date: December 2013

Abstract
U-Pb isotopic analyses have been carried out on calcite vein material and its carbonate host rock collected at surface and from drill core in the area of the Bruce nuclear site. The U-Pb data are used to constrain ages of calcite growth and therefore determine the timing of fracture formation and fluid mobility within these rocks. Analyses were carried out by laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) and by isotope dilution thermal ionization mass spectrometry (ID-TIMS). LA-ICPMS dating is relatively imprecise, with errors of about 5-10 Ma, but allows material to be sampled at the 100 micron scale. ID-TIMS requires much larger samples but is more precise with errors of 1-2 Ma or better on single analyses in favourable cases.

Previous studies have revealed a number of differently oriented fracture sets within the Devonian carbonate rocks of the Lucas Formation exposed at surface. LA-ICPMS dating shows that veins of different orientation share the same pattern of ages. This pattern is characterized by a broad peak of ages around 110 Ma with a minor peak around 56 Ma. ID-TIMS data from surface samples appear to confirm the pattern of two ages shown by the LA-ICPMS data and suggest that calcite growth took place over a protracted period from at least 110-85 Ma with reactivation at approximately 50 Ma. The comparability of ages yielded using the two methods supports the reliability of the results.

Data on calcite in veins collected from drill core samples of the Lucas Formation at a vertical drill length of 34 m below ground surface indicate a similar age pattern to surface veins. These near-surface calcite veins contain U concentrations generally in the range of 1-10 ppm with moderately to highly radiogenic Pb. Conversely, calcite-filled veins in drill core samples from the deeper Ordovician formations are generally thinner (hairline- to mm-scale apertures) than surface and near-surface veins and the analysed material shows order of magnitude lower U concentrations and less radiogenic Pb. Only a small number of deep Ordovician samples, including one from the Collingwood Member of the Trenton Group and one from the Coboconk Formation of the Black River Group, met the criteria in terms of isotope concentrations needed to provide meaningful ages. Age determinations from these samples are less precise but the data suggest a much older age for fracture formation and vein emplacement (445 ± 42 Ma) that approaches the Paleozoic depositional age of the host rock and also overlap the range of time expected for events related to the Taconic Orogeny.

The data suggest that the calcite veins in the deep Ordovician Trenton and Black River groups were formed in the Paleozoic era shortly after deposition of the host rock. Fracturing and emplacement of the calcite veins within the Devonian Lucas Formation appears to have occurred during the middle Cretaceous with additional calcite crystal growth during the early Paleogene. No evidence is seen for more recent (e.g., Pleistocene) vein calcite growth in either the shallow Devonian or deep Ordovician formations.

ABSTRACT

Title: Sorption Studies with Sedimentary Rock Under Saline Conditions
Report No.: NWMO TR-2013-22 (In Progress)
Author(s): P. Vilks and N.H. Miller
Company: AECL
Date: December 2013

Abstract
Batch sorption tests were performed for the elements Li(I), Ni(II), Cu(II), Pb(II), Zr(IV) and U(VI) with Canadian sedimentary rocks (shale and bentonite) and bentonite and the SR-270 reference brine solution (TDS = 275 g/L). The SR-270 brine contains Na, Ca, Cl, K, Mg, and a number of other minor elements to approximate natural brine. Batch sorption tests were also performed with a dilute reference solution (TDS = 0.64 g/L), containing millimolar amounts of Na, Ca, Cl and HCO_3, to provide a reference case where sorption would not be suppressed by the presence of high salt concentrations. The sorption data obtained from this study contribute to the development of a database of sorption coefficients (K_d values) for Canadian sedimentary rocks and bentonite in highly saline solutions.

Batch sorption tests were performed for time periods up to 127 days using both single elements (U and Zr) and solutions containing multiple elements (Li, Ni, Cu, Pb and U). The sorption K_d values of divalent elements Ni, Cu and Pb were 1 to 3 orders of magnitude lower in the brine than in the dilute reference solution. Comparison sorption tests performed under sterile and normal laboratory conditions showed that sorption measurements in the brine solution were not affected by the presence of microbes in the laboratory. Short term (1h) sorption tests showed that the sorption of U(VI), Cu and Zr increased with pH. Desorption tests performed for U indicated that although desorption does occur, the sorption process is not completely reversible. When desorption was initiated the apparent K_d values were factors of 5 to 7 higher than before desorption. After 55 days of desorption these apparent K_d values remained at a factor 2 higher than before desorption.

Using montmorillonite and illite to approximate bentonite and shale (with 60% illite), surface complexation modelling was performed for these minerals using a 2-site protolysis non-electrostatic surface complexation and cation exchange model. In the SR-270 reference brine, where sorption is dominated by surface complexation, the literature derived surface complexation constants for Ni produced simulated K_d values that matched measured values. In the cases where surface complexation constants were estimated using linear free energy relationships (LFER), simulated K_d values were within measured values by factors of 1.5 to 1.7 for Cu, 1.2 to 3.4 for Pb, and 1.6 to 3.0 for Zr. In the dilute reference solution, where cation exchange dominates, simulated K_d values for Ni, Cu and Pb were within measured values by factors of 1.5 to 3.3. The agreement between simulated and measured K_d values provides confidence that sorption models might be used to provide a reasonable estimate of the sorption properties of elements for which experimental sorption data are not yet available in brines.

Diffusive and advective mass transport tests were performed with Queenston shale samples and the SR-270 brine to study the sorption and migration properties of Li, Ni, Cu, Pb and U in shale. The K_d values derived from the batch tests are consistent with K_d values estimated from the diffusive mass transport experiments in shale, providing confidence that the sorption K_d values obtained from the batch sorption tests can be applied to account for sorption in mass transport within shale. This suggests that an equilibrium approach using K_d values can be used to simulate diffusive mass transport in shale without requiring the use of sorption kinetics.

Dynamic transport (i.e. advective transport) tests improve our understanding of the role of sorption in mass transport, and can be used to estimate sorption coefficients despite uncertainties associated with mass transport processes.

ABSTRACT

Title: Matrix Porewater in Crystalline Rocks: Extraction and Analysis
Report No.: NWMO TR-2013-23
Author(s): F. Eichinger and H.N. Waber
Company: HydroIsotop and University of Bern
Date: December 2013

Abstract
The chemical and isotopic characterization of porewater residing in the inter- and intragranular pore space of the low-permeability rock matrix is an important component with respect to the site characterization and safety assessment of potential host rocks for a radioactive waste disposal.

The chemical and isotopic composition of porewater in such low permeability rocks has to be derived by indirect extraction techniques applied to naturally saturated rock material. In most of such indirect extraction techniques – especially in case of rocks of a porosity below about 2 vol.% – the original porewater concentrations are diluted and need to be back-calculated to in-situ concentrations. This requires a well-defined value for the connected porosity – accessible to different solutes under in-situ conditions. The derivation of such porosity values, as well as solute concentrations, is subject to various perturbations during drilling, core sampling, storage and experiments in the laboratory.

The present study aims to demonstrate the feasibility of a variety of these techniques to characterize porewater and solute transport in crystalline rocks. The methods, which have been developed during multiple porewater studies in crystalline environments, were applied on four core samples from the deep borehole DH-GAP04, drilled in the Kangerlussuaq area, Southwest Greenland, as part of the joint NWMO–Posiva–SKB Greenland Analogue Project (GAP).