Technical Program for Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2016

NWMO-TR-2017-01 **December 2017**

R. Crowe, K. Birch, J. Freire-Canosa, J. Chen, D. Doyle, F. Garisto, P. Gierszewski, M. Gobien, C. Boyle, N. Hunt, S. Hirschorn, M. Jensen, P. Keech, L. Kennell-Morrison, E. Kremer, C. Medri, M. Mielcarek, A. Murchison, A. Parmenter, E. Sykes, T. Yang

Nuclear Waste Management Organization

NUCLEAR WASTE MANAGEMENT ORGANIZATION
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ABSTRACT

Title: **Technical Program for the Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2016**
Report No.: **NWMO-TR-2017-01**
Author(s): R. Crowe, K. Birch, J. Freire-Canosa, J. Chen, D. Doyle, F. Garisto, P. Gierszewski, M. Gobien, C. Boyle, N. Hunt, S. Hirschorn M. Jensen, P. Keech, L. Kennell-Morrison, E. Kremer, C. Medri, M. Mielcarek, A. Murchison, A. Parmenter, E. Sykes, T. Yang
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Abstract
This report is a summary of activities and progress in 2016 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 the long-term management of used nuclear fuel. Significant technical program achievements in 2016 are summarized below.

- NWMO continued to participate in international research activities associated with the SKB Äspö Hard Rock Laboratory, the Mont Terri Underground 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's research program published 14 NWMO technical reports, submitted 11 papers for journal publication and 17 abstracts for presentation at national and international conferences focused on environmental radioactivity and radioactive waste management.

- 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 case studies and methods for detailed site investigations in both crystalline and sedimentary rock in the fields of: geology, hydrogeochemistry, isotope geochemistry, paleohydrogeology, sub-surface mass transport, geomechanics, seismicity, geochronology, microbiology and long-term climate change.

- 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. The finalized conceptual design for a DGR is illustrated in Figure 1-1. Work conducted and progress made within the APM Technical R&D Program during 2016 is summarized in the remainder of this report. A brief update on the status of NWMO's site selection process is provided below.

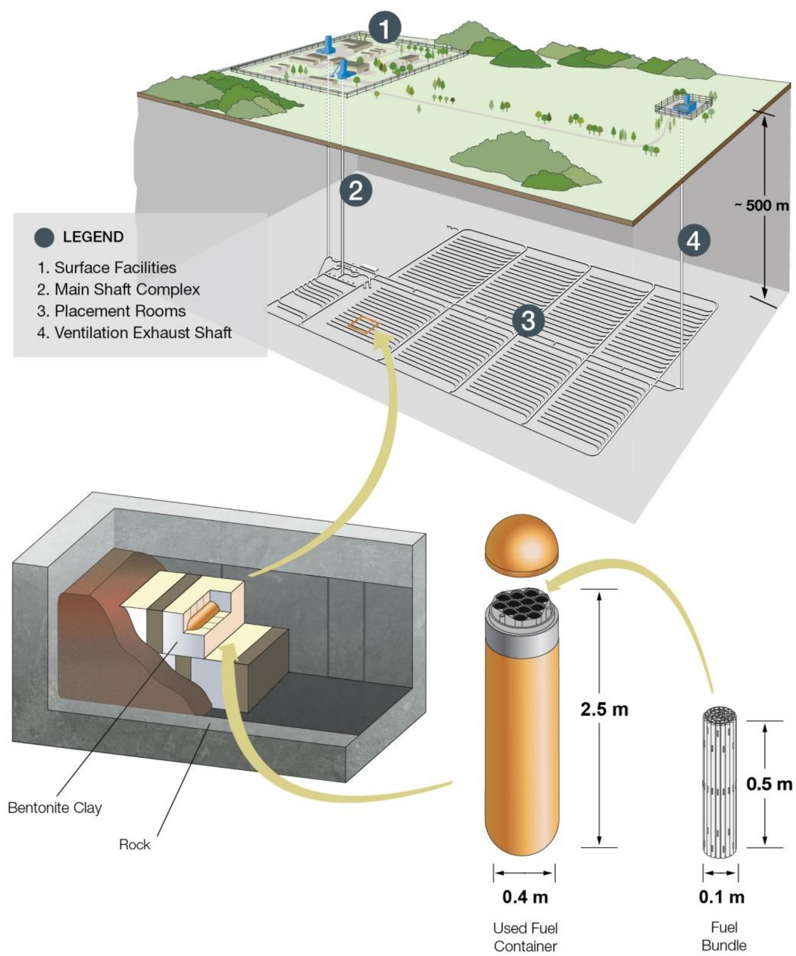


Figure 1-1: Illustration of a Deep Geological Repository Reference Design

1.1 SITE SELECTION PROCESS

On September 30, 2012, the NWMO suspended accepting new expressions of interest from potential host communities. A total of 22 communities had expressed interest in the program at this time, of which 21 passed the initial screening step (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) preliminary assessments 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 site based on detailed site evaluation criteria. Each step is designed to evaluate the site in greater detail than the previous step.

NWMO completed 22 Initial Screening studies, and the initial screening reports are published on NWMO's site selection website (http://www.nwmo.ca/sitingprocess). By 2016 the number of communities engaged in the site selection process had been narrowed to 9, based on preliminary desktop assessments of potential geological suitability and potential for the project to contribute to community well-being. The status of each community as of December 2016 is shown in Figure 1-2.

All reports completed are published on the NWMO's site selection website (http://www.nwmo.ca/sitingprocess_feasibilitystudies).

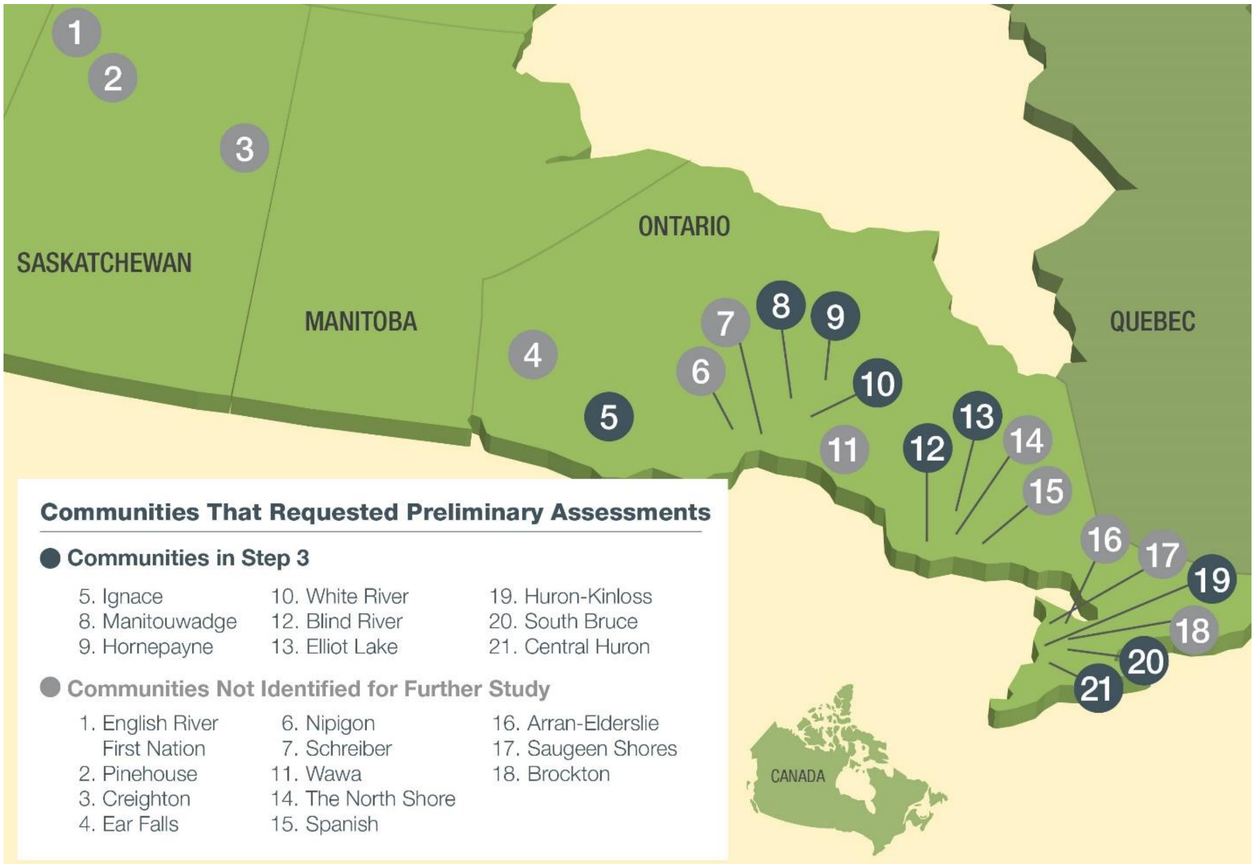


Figure 1-2: Communities Expressing Interest in the APM Siting Process and Current Status (December 31, 2016)

2. OVERVIEW OF CANADIAN RESEARCH AND DEVELOPMENT PROGRAM

2.1 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 for detailed site characterization in a 2023 timeframe.

To support the primary objective of the APM Technical Program, the following Technical Program objectives have been developed and are broken down into 4 groups.

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 2016 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 2014 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, 2014, 2015, 2016). 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 the primary external contractors and collaborators for the technical work programs.

2.2 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, the 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 2016, NWMO continued to participate with POSIVA and SKB on the POST Project (Fracture Parameterization for Repository Design & Post-closure Analysis in the Äspö and ONKALO HRL).

Since 2008, the NWMO has been a partner in the Mont Terri Project, which consists of a series of experiments carried out in the Mont Terri Underground Rock 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, the NWMO continues to be involved in the following experiments:

- Diffusion, Retention and Perturbation (DR-A);
- Long-term Diffusion (DR-B);
- Microbial Activity (MA);
- Iron Corrosion in Opalinus Clay (IC);
- Iron Corrosion – Bentonite (IC-A);
- Long Term Pressure Monitoring (LP-A);
- Hydrogen Transfer (HT);
- Deep Borehole Experiment (DB);
- Full Scale Emplacement Experiment (FE-G, FE-M).

In order to advance 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 the national nuclear waste management organisations in Sweden (SKB), Finland (Posiva) and Canada (NWMO). The primary aims of the GAP were to enhance scientific understanding of glacial processes and their influence on both surface and subsurface environments relevant to deep geological repository (DGR) performance in crystalline shield rock settings. Based on its size, relative accessibility, and crystalline shield bedrock, the Greenland Ice Sheet (GrIS) was selected by the GAP as a natural analogue for glaciation processes expected to recur in Fennoscandia and Canada over DGR safety-relevant timeframes. The scientific understanding of glacial hydrological processes attained through the GAP was documented in a two-volume set of Greenland Analogue Project final reports in 2016 (NWMO-TR-2016-12 and NWMO-TR-2016-13). The NWMO is collaborating with Nagra, SKB and Posiva on an ice drilling project to establish new constraints on the impact of ice sheets on groundwater boundary conditions at the ice-bed contact. The work uses detailed field studies of the Greenland ice sheet, as part of a larger National Science Foundation (NSF) project looking at ice dynamics, for in-situ observations of bed conditions. This project focuses on three aspects of boundary conditions that ice sheets place on groundwater systems. These aspects are: 1) testing for transient high water pressure pulses; 2) establishing bed water pressure gradients at the relevant scale of ice thickness; and, 3) constraining the flooding and transmissivity of water across the bed. The ice drilling project will run through the end of 2017, with a final report planned for publication at project completion.

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.

The NWMO also continued its participation in BIOPROTA, the international working group on biosphere modelling. In 2016, the NWMO continued its contribution to the funding of three BIOPROTA projects, in partnership with other waste management organizations:

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

3. REPOSITORY ENGINEERING

Research and development progressed in the Repository Engineering program during 2016 and primary areas of work included: used fuel recovery and transport, used fuel container design, fabrication and corrosion tests, buffer and sealing systems, and microbial studies of the sealing systems. Summaries of these activities are provided in the following sections.

3.1 USED FUEL TRANSPORTATION

3.1.1 Preliminary Analysis of Basket Transportation Package Concept

In 2016, a new conceptual design was produced for the radioactive material transportation package. The Basket Transportation Package (BTP) concept was designed to carry used nuclear fuel from Point Lepreau and Gentilly-2 nuclear power generating stations. The BTP concept is a cylindrical package designed to accommodate round baskets designed by Atomic Energy of Canada Limited (AECL). NWMO's current fleet of certified transportation packages are optimized for fuel modules designed by Ontario Power Generation. The BTP concept was designed to expand NWMO's fleet, i.e., to be able to carry used fuel in AECL-style round baskets in addition to the OPG rectangular modules. This year, the BTP concept was analyzed using advanced computer simulation tools. Two aspects of the BTP concept were studied: 1) radiation shielding capability, and 2) performance in hypothetical accident conditions that could be associated with transport.

The radiation shielding capability of the BTP concept was analyzed using Monte-Carlo N-Particle (MCNP) software at International Safety Research (ISR) Inc. MCNP is a sophisticated simulation tool for radiation transport and is a nuclear-industry standard. The analysis simulated both gamma and neutron radiation fields for conservative payloads. Shielding capability for both normal and accident conditions of transport were studied. In all cases, the external radiation dose levels associated with the BTP concept were found to satisfy CNSC regulatory limits.

The shielding analysis also included a shielding thickness sensitivity study. Such a study helped NWMO designers understand the effect of shielding thickness on external radiation dose levels. This understanding will help NWMO designers further optimize the BTP concept through its next design phase.

CNSC regulations require that safety be designed directly into Type B (U) packages like the BTP concept. This ensures transportation accidents do not release radioactive materials and expose the public to radiation. As such, the BTP concept must be designed to withstand very severe transportation accident conditions. The robustness of the BTP concept was analyzed using the ANSYS simulation software at Nuvia Canada Inc., in parallel with an NWMO in-house analysis. ANSYS consists of a suite or simulation/analysis tools and is an engineering-industry standard. In particular, ANSYS LS-DYNA and ANSYS Mechanical were used in the analysis summarized below. The analysis simulated dropping the BTP from a 9 metre height onto a rigid unyielding surface, dropping it one metre onto a rigid pin, and subjecting it to a fully engulfing 800°C fire for 30 minutes (see Figure 3-1). These simulations constituted the severe set of hypothetical accident conditions of transport tests specified in CNSC regulations. The results are being used to improve the design and complete the preliminary design phase.

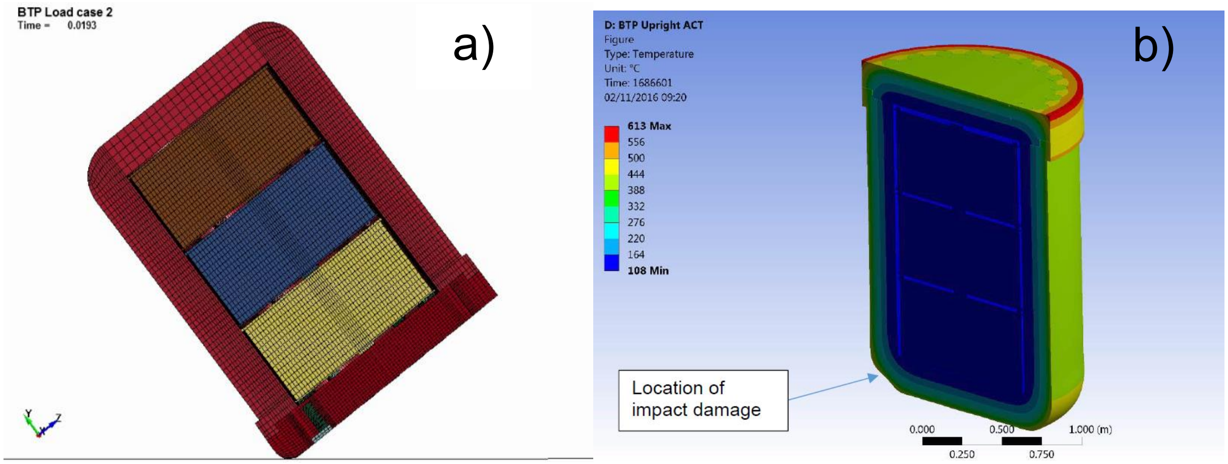


Figure 3-1: Computer Simulation of BTP Concept: Impact Test (a) and Thermal Test (b)

3.1.2 Advanced Materials Research

Radiation shielding and impact protection are major elements of consideration when developing the used nuclear fuel transportation package. Transportation packages are typically made from steel, which provides excellent gamma shielding but relatively poor neutron shielding. Depending on the characteristics of the package content, it is sometimes prudent to add neutron shielding. Adding such material to a package may increase its weight beyond practical weight limits for road transportation. There is potential opportunity to replace existing package component material with material that provides neutron shielding as well. One such component is the impact limiter, a helmet-like component designed to crush and to absorb energy in an impact accident. Impact limiters are typically filled with a crushable foam inner core. The NWMO investigated alternative impact-limiter core materials and has identified carbon aerogels as a potential replacement option. The low density of aerogels provides potential weight reduction of the BTP. The highly flexible and customizable aerogel synthesis process may allow an increase in shielding capability of the BTP by including both hydrogen and boron in the matrix to increase neutron absorption capability.

The NWMO began a collaboration with Lawrence Livermore National Laboratory (LLNL) on an experimental program to assess the energy absorption capabilities of standard carbon aerogel material during impacts. In this experimental program, the energy absorption characteristics of aerogel will be compared against polyurethane foams, the more commonly used material in impact limiters. Results will help NWMO designers to further optimize current package designs and help inform future designs of new transportation packages.

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

The mobile exhibit trailer for the UFTP continued to serve as an excellent means to demonstrate transportation package robustness. In 2016, the exhibit was taken to 14 public engagement events, spanning 20 days. Through these engagement events, the public is able to access the exhibit and have a chance to both see and feel the massive size, weight, and strength of the UFTP. In addition, technical experts staffing the exhibit invited the public to ask questions about used fuel transportation, the overall project, and the NWMO (Figure 3-2). When not being used at engagement functions, the exhibit was housed at the NWMO's Engineering Facility in Oakville, Ontario, where it was set up in display mode for a number of tours held in 2016.

Planned improvements to the mobile exhibit in 2016 included: updating components to improve efficiency and safety of the set-up and tear-down processes; installing solar power system to reduce reliance on generator power and reduce carbon emission footprint; and installing retractable awning over the display deck to improve comfort for both the staff and public.

Figure 3-2: Mobile Exhibit Trailer for the Used Fuel Transportation Package

3.1.4 Understanding Radiation Dose

Radiation exposure is a natural part of everyday life. People are exposed to low levels of radiation every day from many sources including natural background radiation, medical procedures, flying in airplanes, elements within our bodies, and even some objects around our homes. The international System of Units (SI) uses the Sievert (Sv) as the unit to express health effects of low levels of radiation. However, the Sievert is not a commonly understood unit. A more relatable way to understand radiation dose was developed by NWMO staff, which involves converting abstract units of Sieverts into understandable units of time. This Flight-time Equivalent Dose (FED) presents radiation dose values in terms of equivalent air time (i.e., in terms of time spent flying in a typical commercial aircraft). For example, the dose from a typical dental x-ray, of 0.01mSv, is approximately equivalent to the dose received during a 2.5 hour flight and can thus be expressed as equivalent to 2.5 flight-hours, or 2.5 h FED (see Figure 3-3). Other interesting examples are: eating a banana is equivalent to 1.5 flight-minutes; sleeping next to a partner nightly for a whole year is equivalent to 5 flight-hours; annual background radiation in Toronto is equivalent to 400 flight-hours; and the CNSC public radiation dose limit is equivalent to 250 flight-hours. Relating radiation dose to equivalent time spent in a commercial aircraft provides a versatile, accessible, standardized context for evaluating and understanding radiation dose.

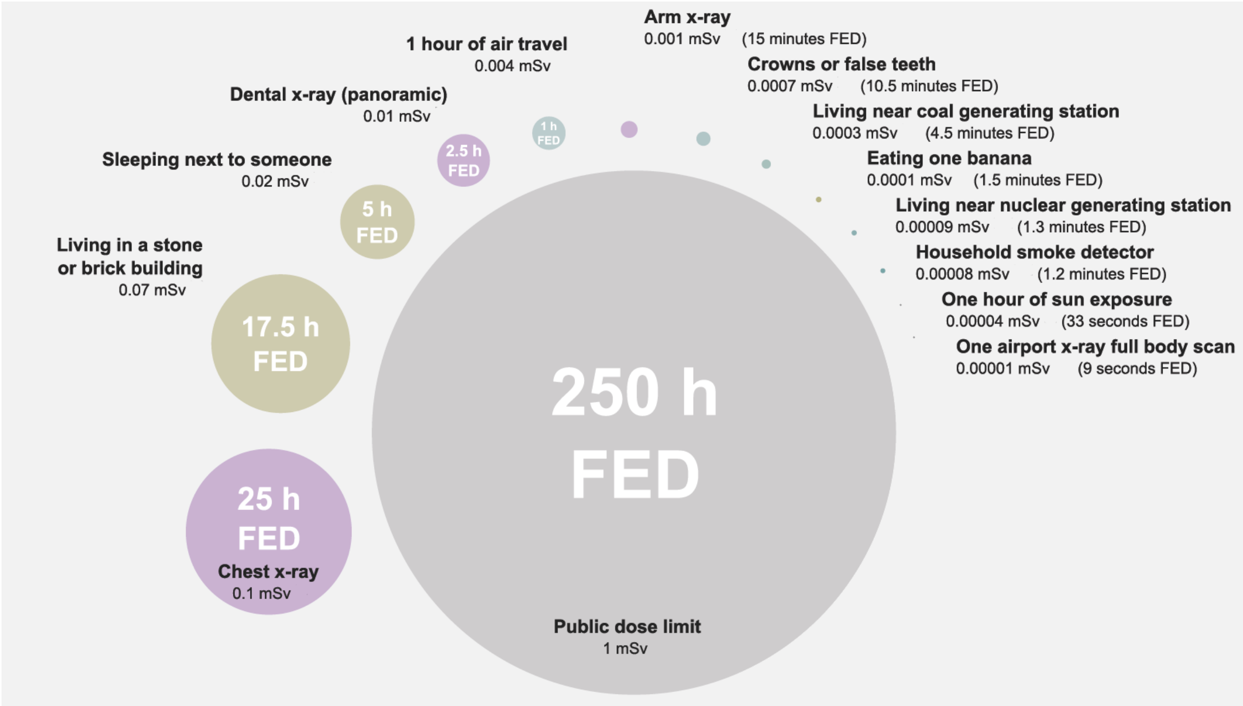


Figure 3-3: Flight-time Equivalent Dose Examples

3.1.5 Testing Transportation Packages in Extra-Regulatory Conditions

Transportation packages are subjected to stringent regulatory tests. Hypothetical accident conditions aim to simulate and bound any reasonable real-world accident scenarios. However, the severity of the regulatory tests are difficult to appreciate and difficult to communicate to the public. NWMO has begun developing capabilities to simulate tests that, from the perspective of the public, more closely resemble real-world scenarios and allow for a more demonstrative confirmation of package integrity.

One such area of development is the computational fluid dynamics (CFD) simulation of realistic fire scenarios. Fire is a highly complex and dynamic physical phenomenon. Modelling of this complex phenomenon is typically done through equations and correlations developed through experimentation. However, correlations, like the regulatory tests, are difficult to appreciate and communicate to the public. Equations lack the visual impact compared to photos of real-world fire accident scenes. Therefore, the NWMO worked on simulating the dynamic combustion chemistry within fires, the turbulent mixing of fuel with air, and the dynamic heat output of fires. Such simulations look and feel more realistic. The NWMO worked on tuning the CFD combustion simulation models and validating against real-world fire tests (see Figure 3-4). Once validated, the CFD combustion simulation model will be used to simulate a variety of large-scale fire accident scenarios and the performance of transportation packages under such conditions (Sui 2016).

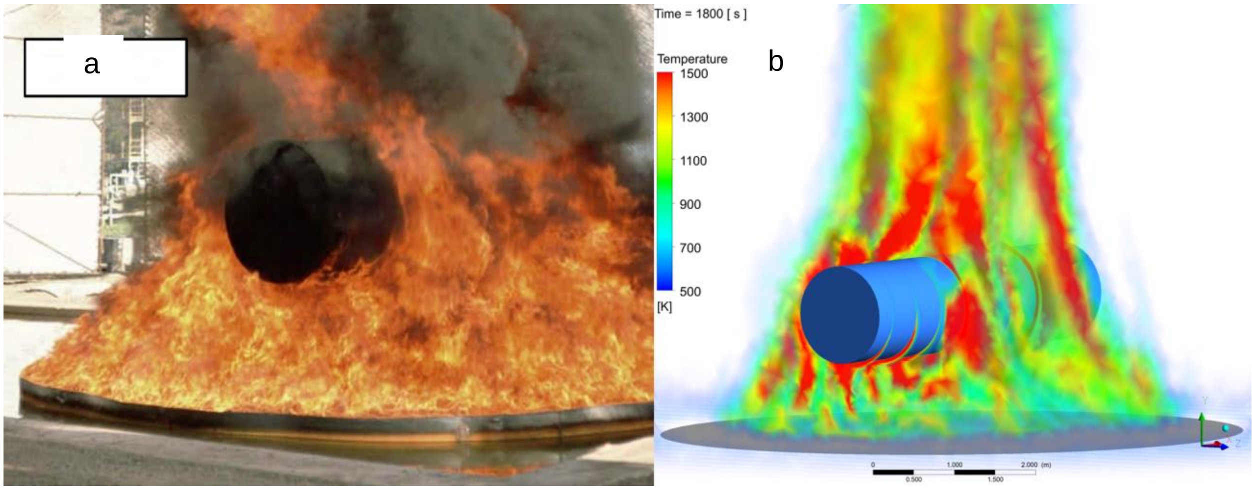


Figure 3-4: Simulating (a) Real-world Fire Test with (b) CFD Combustion Simulation

3.1.6 PATRAM: Packaging and Transportation of Radioactive Materials Conference

Two NWMO representatives attended and presented at the 18th International Symposium on the Packaging and Transport of Radioactive Materials (PATRAM) in Kobe, Japan. PATRAM is a triennial (once every three years) gathering of international experts on radioactive material transport. Both NWMO presentations were well received. The NWMO representatives each won awards at the symposium (best poster presentation, best paper presentation) for work on the FED (Section 3.1.4) and CFD combustion simulation (Section 3.1.5), respectively.

3.2 USED FUEL CONTAINER (UFC)

In 2016, the NWMO continued the execution of the multi-year Proof Test Program to validate the design and manufacturing technologies for the reference Used Fuel Container (UFC). An illustration of the UFC is shown in Figure 3-5 and a prototype is shown in Figure 3-6.

On the manufacturing front, advancements in both UFC process technology and application equipment are being made in preparation for the initiation of a serial production campaign commencing in 2018. As part of the detailed design stage, the NWMO initiated the preparation of a detailed design specification for the UFC. Also in 2016, the NWMO performed the second full-scale external pressure test on a reference design UFC prototype under simulated glacial loading conditions. The results of these programs are reported in the following sections.

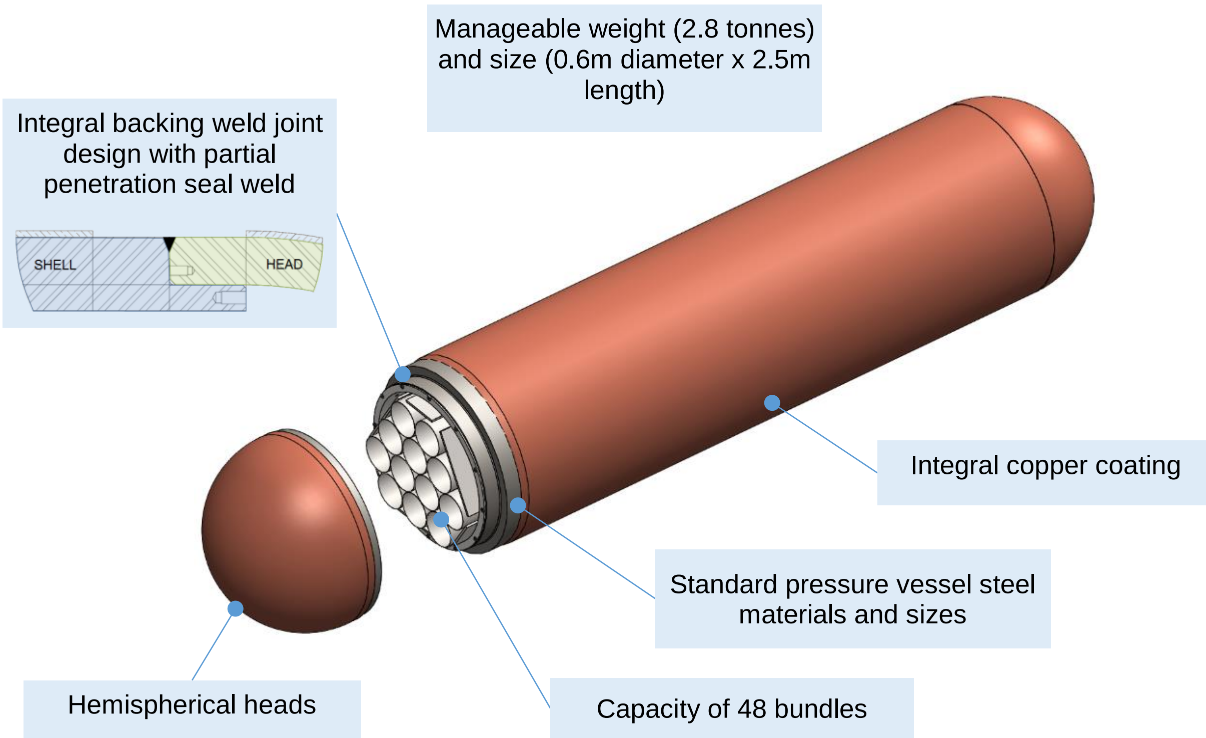


Figure 3-5: Illustration of Used Fuel Container with Design Features Identified

Figure 3-6: Prototype Used Fuel Container after Final Machining

3.2.1 Used Fuel Container Design

NWMO has now completed preliminary design evaluations of the 48 bundle capacity concept UFC. With this vessel now selected as the Reference UFC design, the design has advanced to the detailed design stage. This has included a series of activities, such as the refinement of design requirements, design input collection, preparation of design specifications, design drawing preparation, stress analyses and preparation of design reports.

In 2016, work was initiated on the preparation of a comprehensive UFC Design Specification. This document includes the general description of the UFC design process, selection of applicable code and standards, design requirements, design inputs, design criteria, and a description of the reference design.

Compared with a conventional design specification for nuclear power plant components, the challenge in the preparation of a UFC design specification is that there are no Canadian or international engineering codes or standards specific to the design and construction of permanent disposal containers. Therefore, existing national and international codes and standards were reviewed and selectively adopted for the UFC design. The loading conditions were identified and the design inputs were compiled based on the research that the NWMO has conducted to-date. Design criteria for the UFC structural vessel and the corrosion barrier were established by combining the applicable portions of the existing codes, peer experience, and alternative design methods based on sound engineering principles. This information, together with the presentation of the UFC reference design parameters, form the design basis of this unique application of nuclear waste disposal containment.

3.2.2 Used Fuel Container Manufacturing

3.2.2.1 Closure Welding

The UFC components (shell and hemi-spherical heads) are assembled using an advanced Hybrid-Laser-Arc-Welding (HLAW) technique. The geometry of the UFC requires that it is rotated during welding and weld cap machining. The ancillary equipment that is used to conduct this operation is referred to as the “ROTEQ”.

In the execution of NWMO’s UFC weld development program, a first generation “proof-of-concept” or “Alpha” ROTEQ was built in 2015 by NWMO’s welding technology vendor (Novika Solutions) and utilized in the fabrication of UFC prototypes. “ROTEQ 1.0” achieved rotation of the UFC through the use of a tail and head stock clamping mechanism, applied to the hemi-spherical heads of the UFC. Results from the prototype fabrication campaigns identified limitations with the ROTEQ 1.0 design with respect to achieving the required stability and control for performing both welding and machining operations. In 2016, design work was initiated on an alternate “ROTEQ 2.0” concept for advancement as the second generation or “Beta” design. This concept utilizes a mechanism to clamp and rotate the UFC from within the cylindrical shell area. An illustration of this equipment is shown in Figure 3-7(a, b). Detailed design, fabrication and commissioning of ROTEQ 2.0 is scheduled for 2017.

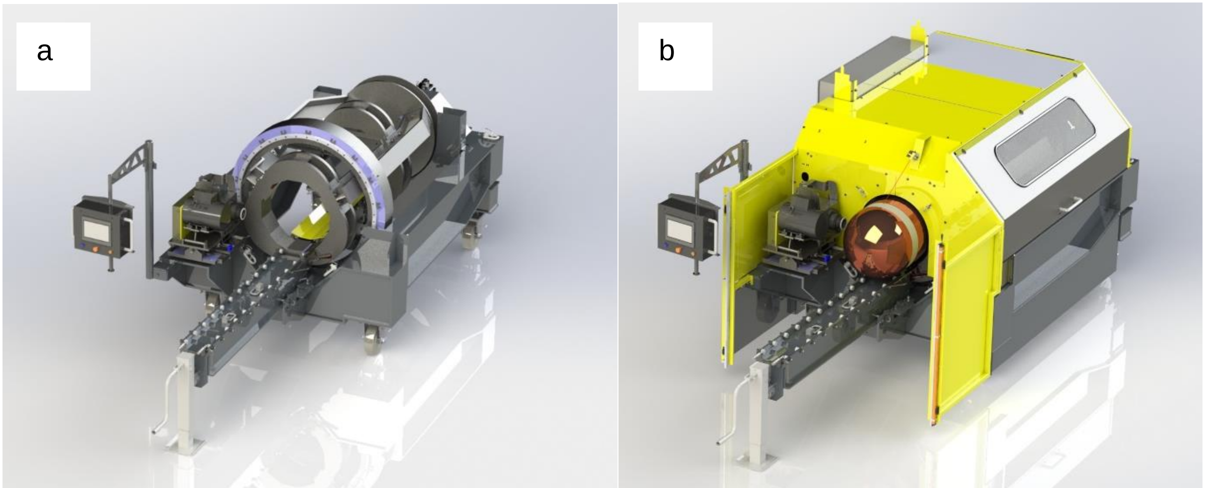


Figure 3-7(a, b): Illustration of Second Generation Ancillary Equipment (ROTEQ 2.0) Used to Rotate UFC during Closure Welding

3.2.2.2 Copper Coating Development

In 2016, NWMO continued the development of copper coating technologies for the UFC external surface corrosion barrier. After a successful scale-up of both electrodeposition and cold spray processes for the application to prototype UFC's in previous programs, a manufacturing optimization effort at the pilot scale has been initiated. The manufacturing optimization efforts will be essential in preparation for the serial-production campaign planned to start in 2019. The main objective will be to refine the two technologies with respect to manufacturing methods, using equipment that is amenable for serial production.

3.2.2.3 Electrodeposition Copper Coating Technology

Since 2012, the NWMO has conducted a multi-phased program with the vendor Integran Technologies for development of copper electrodeposition technology via the use of a pyrophosphate (solution chemistry) system. This program has resulted in the acquisition of baseline data, process optimization and technology transfer to prototype UFCs. In previous years, the NWMO and Integran have demonstrated the suitability of the method for producing a range of copper coated samples, from small-scale (i.e., coupon size) through to full-sized hemispherical heads and lower assemblies.

In early 2016, Integran produced four hemi-spherical heads and two lower assemblies (i.e., shell welded to lower hemi-spherical head) as part of a proof-of-concept demonstration of the process and its ability to reliably produce copper coatings on the respective components. The proof of concept line is shown in Figure 3-8. It consists of a pre-treatment process that includes a series of surface cleaning steps, followed by the application of a "strike" layer of copper prior to applying the required thickness using the pyrophosphate system. Figure 3-9 shows the parts as they are processed. After electrodeposition, the parts are sent for machining and final assembly. It should be noted that components which were copper coated in the early part of 2016 were used in the assembled UFC for external pressure testing later that year.

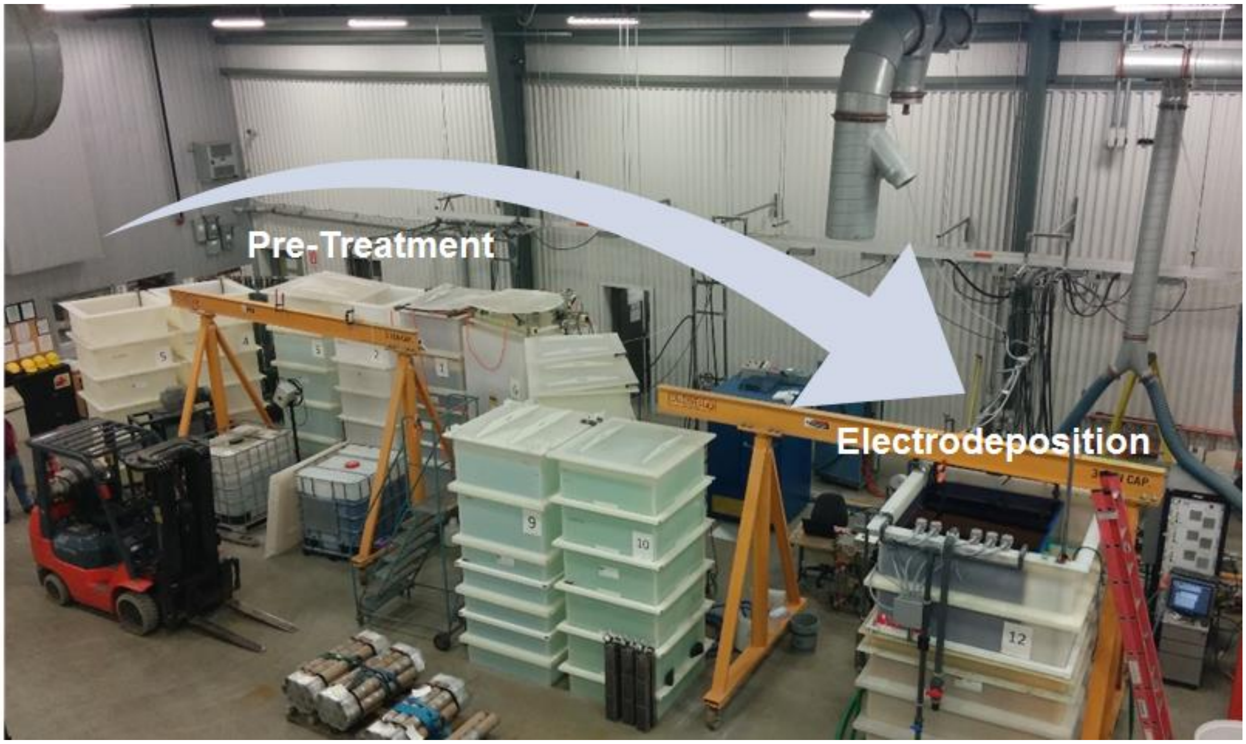


Figure 3-8: Proof-of-concept Line Consisting of Pre-treatment and Electrodeposition Process Tanks

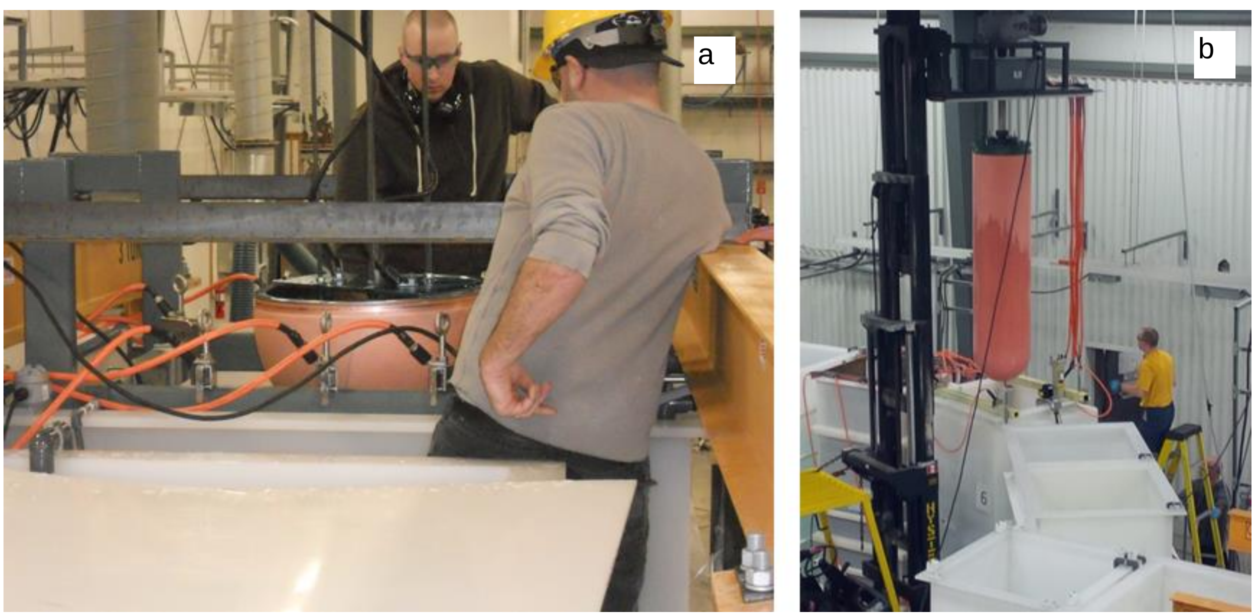


Figure 3-9: UFC Components Being Processed – Hemi-spherical Head (a) and Lower Assembly (b)

In the second half of 2016, a new program with Integran was launched to optimize the manufacturing process in support of the upcoming serial production campaign. Integran initiated the scaling process from the proof-of-concept line to a fully-operational pilot line. This included devising a layout plan, relocation of the line within their facility to a dedicated space, and procurement/installation of key equipment (e.g., tanks, pumps, power supplies, etc.). Figure 3-10 shows the on-going construction of the pilot line.

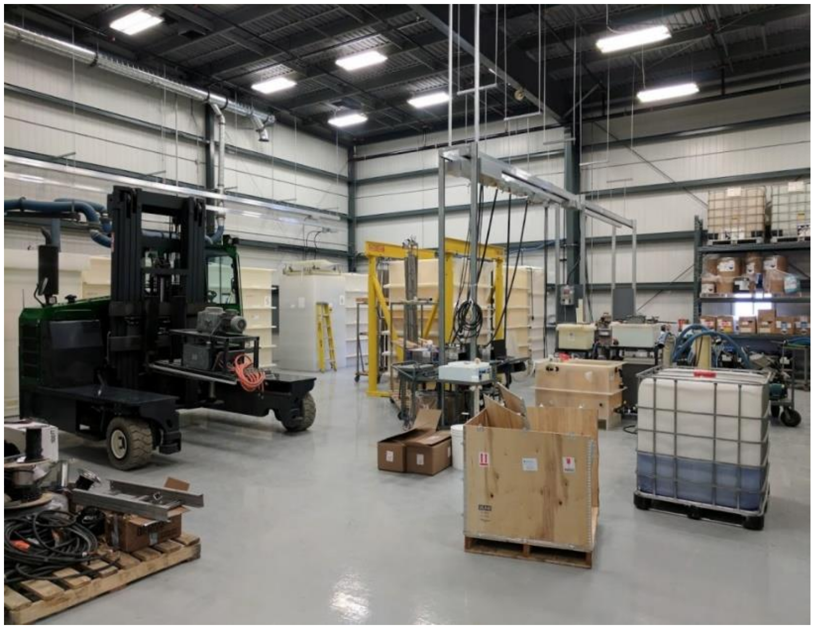


Figure 3-10: In-process Construction of the Pilot Line for Application of Electrodeposited Copper to UFC Components

In parallel to this, efforts were initiated to develop tolerances for the various pre-treatment and pyrophosphate copper electrodeposition processes. This work was performed on a small scale using coupons that would be subjected to various tests, including, purity, adhesion, strength and ductility. The results from this task will be used to identify working limits for critical parameters necessary to keep the process stable and ensure a consistent output. The existing manufacturing and inspection test plan and process manual will be updated accordingly. Figure 3-11 shows the tank and the coupon samples used in these studies.

In 2017, it is expected that all of the tolerance work will be completed and the pilot line will be commissioned to process hemi-spherical heads. The pilot line will eventually be outfitted with a modified existing tank to electrodeposit copper onto hemi-spherical heads and a newly fabricated tank, specifically for electrodepositing lower assemblies. This new tank will be designed during the second half of 2017 and subsequently fabricated, installed and commissioned in the first half of 2018.

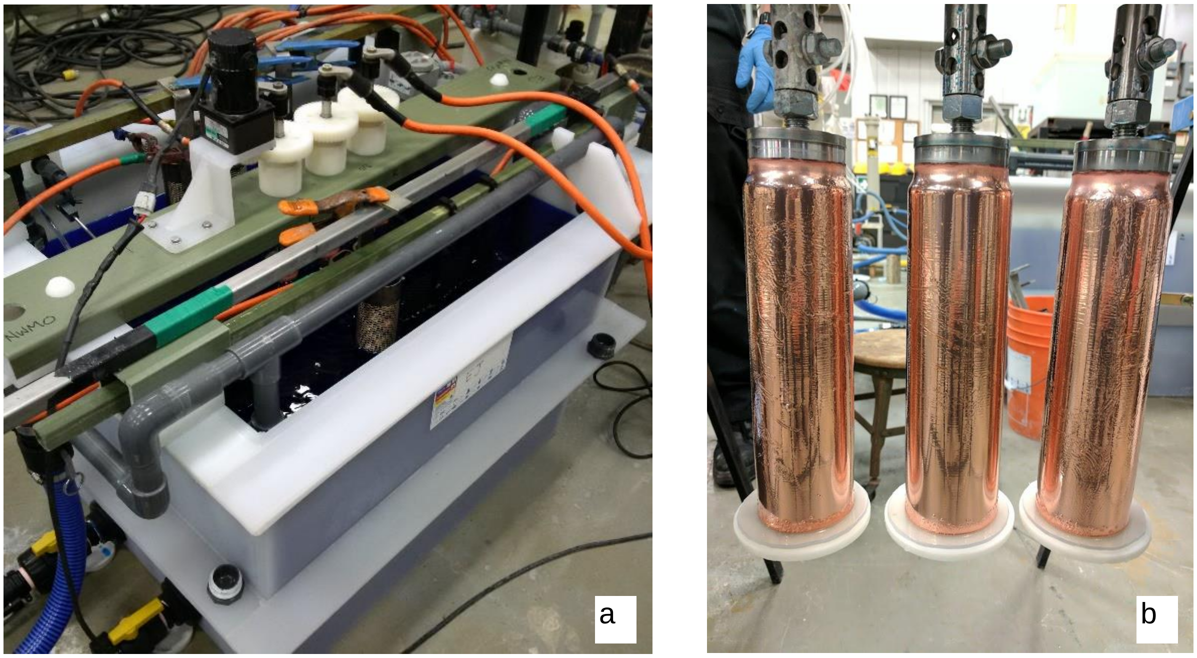


Figure 3-11: Small-scale Tank for Tolerance Studies (a) and Coupons to be Used for Testing (b)

3.2.2.4 Cold Spray Copper Coating Technology

Following the successful development of a copper cold spray method by the National Research Council (NRC) to fully coat UFC components, the NWMO had focused on the adaptation of this coating technique to the UFC closure weld zone. This region is the portion of the UFC that is not coated prior to the loading of used fuel (inside the Used Fuel Packing Plant (UFPP)); the zone undergoes closure via HLAW welding. Following closure and inspection via Non-Destructive Examination (NDE), the coating of this region using the cold spray process completes the application of the external corrosion barrier on the UFC. While cold spray was used on the weld zone of a single UFC in 2014, significant optimization was required prior to implementing this method. During 2015, work focused on important parameters, such as developing a suitable surface preparation of the steel, including the welded and heat affected zones as well as the base metal. The transition zone between the electrodeposited copper and the cold spray regions has been investigated as well, to ensure a suitable bond can be obtained for the cold spray material across all of these components.

At the successful completion of this development program, new efforts were initiated in mid-2016 to optimize and advance the reference process by keeping the selected techniques, while considering that they must be amenable to automation for the envisioned hot cell production environment. In order to first build additional confidence in the application of the process to the closure weld zone, two additional UFCs were prepared using the reference process, which consists of grit-blast preparation of the surface to remove any mill scale. This was followed by a pre-heat to condition the surface using a combination of a high-power lamp and carrier gas at operating temperature and pressure, and finally the copper cold spray process. The two UFCs were intended for external pressure testing to validate the performance of both types of copper coatings under simulated DGR and glacial loading conditions. Figure 3-12Figure 3-12 shows the UFCs as they were processed.

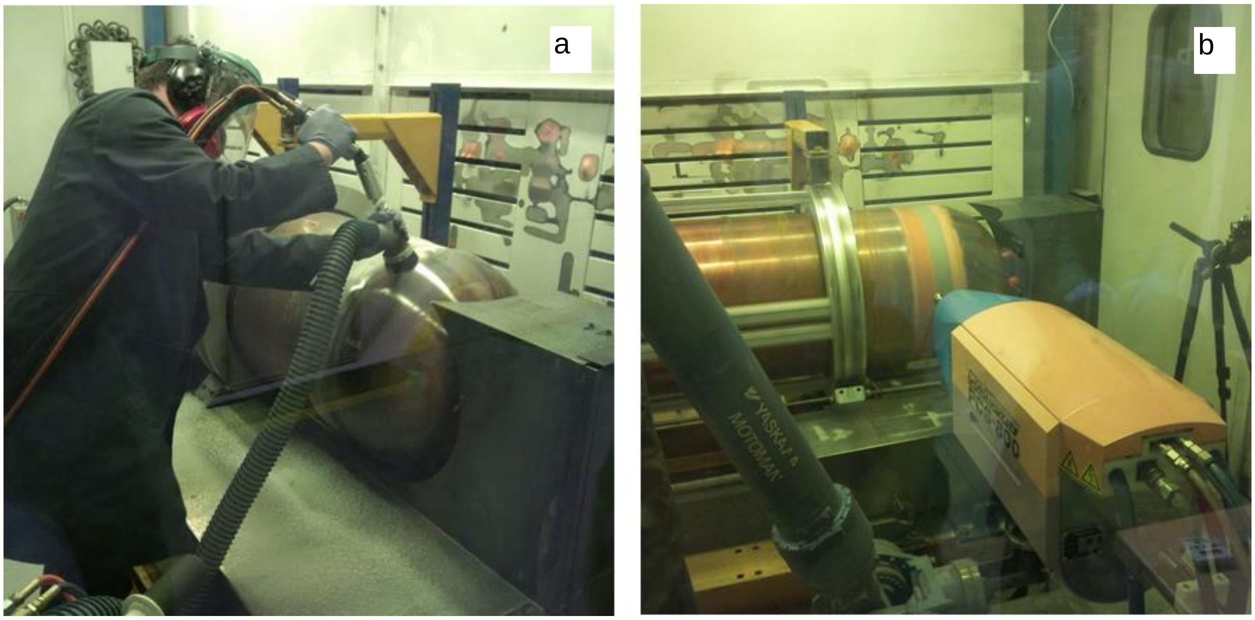


Figure 3-12: Cold Spray of the UFC's – Grit Blasting to Remove Scale (a) and the Application of Cold Spray Copper to the Closure Weld Zone (b)

One critical performance requirement for the coated copper is that it must have sufficient ductility to remain integral to the UFC steel structural core under the loading conditions expected. Cold spray copper in the "as-sprayed" state is known to be relatively brittle, thereby requiring a heat treatment in order to impart a sufficient amount of ductility. In order to achieve this for the UFCs that were intended for the external pressure test, a method for locally heat treating the cold-sprayed copper around the closure weld zone was necessary. For this purpose, a heat band was employed and the ductility was assessed before and after the heat treatment by hardness measurements, which, based on previous work, is expected to decrease; that is, a sufficient decrease in hardness is indicative of achieving a sufficient amount of ductility. With optimization work carried out on pipe segments, the heat band treatment technique was successfully applied to the UFC (Figure 3-13).

During 2016, work was initiated to select and develop techniques that were amenable to automation. In particular, robotic assistance was sought to replace the grit-blasting and heat lamp methods, respectively, for surface preparation and pre-heat or surface conditioning. For surface preparation, a mechanical abrasion technique using a rotary tool on a robot arm was evaluated. Similarly, a high-power laser on a robot arm was also evaluated for its ability to pre-heat or condition the surface. Figure 3-14 shows the robot arm, with the mechanical abrasion tool, and the resulting surface, while Figure 3-15 shows the robot arm, with the laser, as it pre-heats the surface.

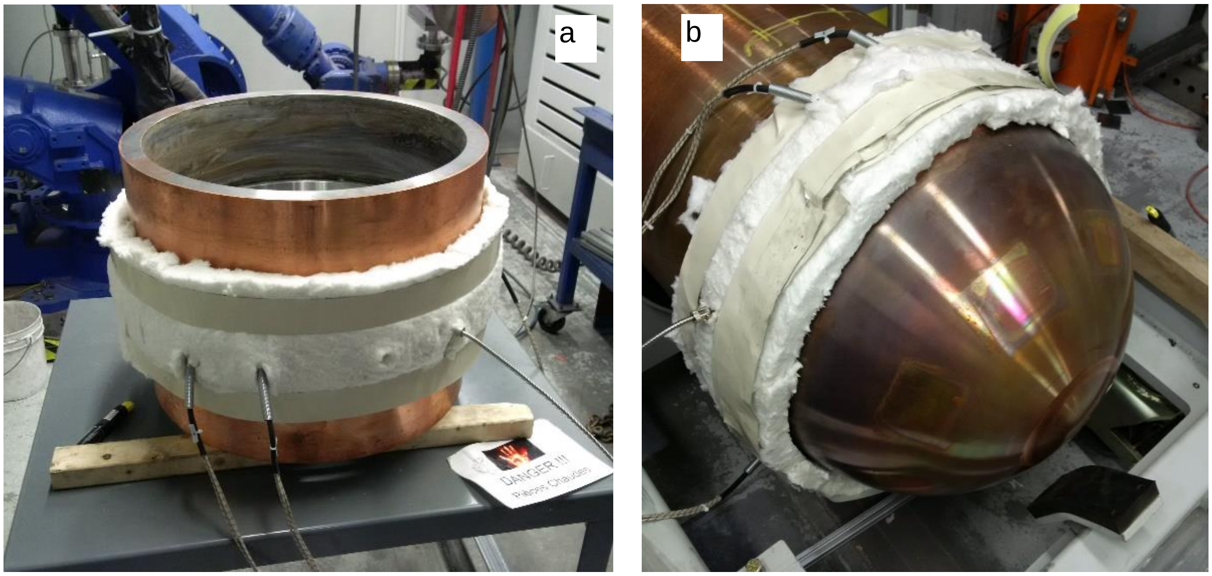


Figure 3-13: Application of Heat Band Treatment Technique to Short Pipe Segments during Optimization (a) and the UFC to be Used for External Pressure Testing (b)

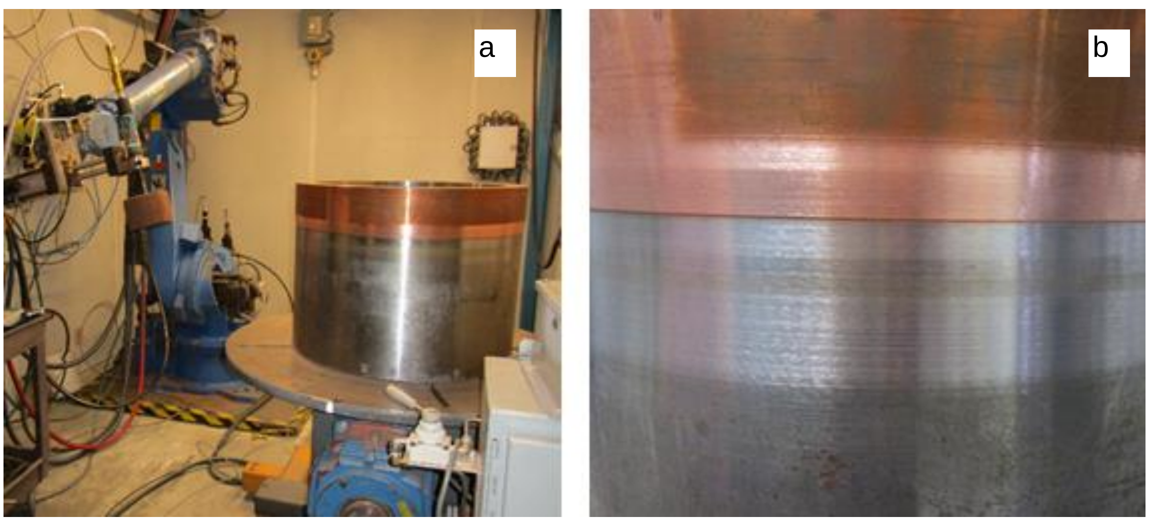


Figure 3-14: Implementation of the Robot-assisted Mechanical Abrasion Tool (a) and Resulting Surface after Removing Scale (b)

Further work will be carried out in 2017 to assess the effects of the new techniques as they relate to adhesion of the copper to the surface. The new techniques will also be applied to mock-up UFCs. The results of this work will lead to an update in the manufacturing and inspection test plan and process manual.

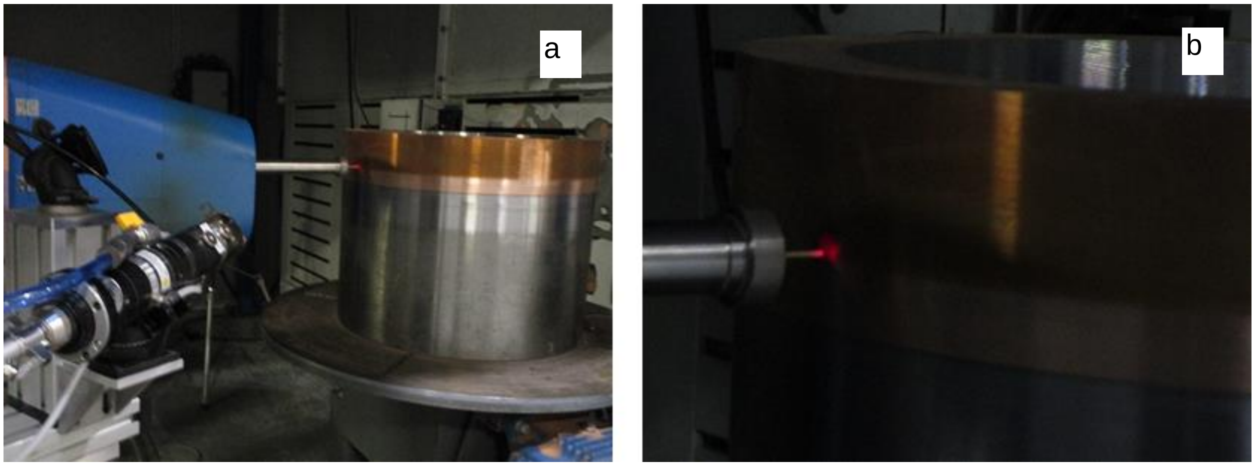


Figure 3-15: Implementation of the Robot-assisted Laser for Pre-heat or Surface Conditioning (a) and Close-up of Laser Spot on the Surface (b)

In parallel to the efforts to automate various aspects of the process, the NWMO (in 2016) has joined a consortium of industry partners hosted by the NRC – whose mandate is to advance cold spray additive manufacturing (CSAM) in various industrial sectors. Within the program, and of particular interest to the NWMO, are efforts directed at automation and cost reduction. In regards to automation, what remains to be advanced is the heat treatment of the as-sprayed copper. Within this program, a laser-assisted heat treatment technique is proposed, which can be very easily automated. For cost reduction, the elimination of the use of helium for the "bond layer" step in the cold spray process is proposed by implementing another laser-assisted operation. Using the learnings from this consortium, the NWMO plans to further develop the techniques for application to the UFCs.

3.2.3 Used Fuel Container Structural Testing

Following the successful full-scale external pressure test of a steel-only prototype UFC in 2015, a similar test was conducted on a copper-coated UFC in 2016. The test was again completed in collaboration with Penn State Advanced Research Lab (ARL) High Pressure Test Facility (HPTF). The ARL HPTF is one of the few places in the world that can simulate pressures up to 45MPa, the theoretical maximum pressure that could be exerted on the UFC during the next ice age.

The objectives of the test were to:

1. Experimentally validate the computer modelling analyses to predict the UFCs response under simulated glacial and collapse (buckling) loads, and
2. Verify the manufacturing and inspection reference processes used in the prototype construction.

Figure 3-16 shows the UFC being lowered into the pressure test vessel with the test vessel lid being subsequently moved into position. As shown, the UFC was instrumented with strain gauges to record the deformation of the vessel in real time as the external pressure was increased.

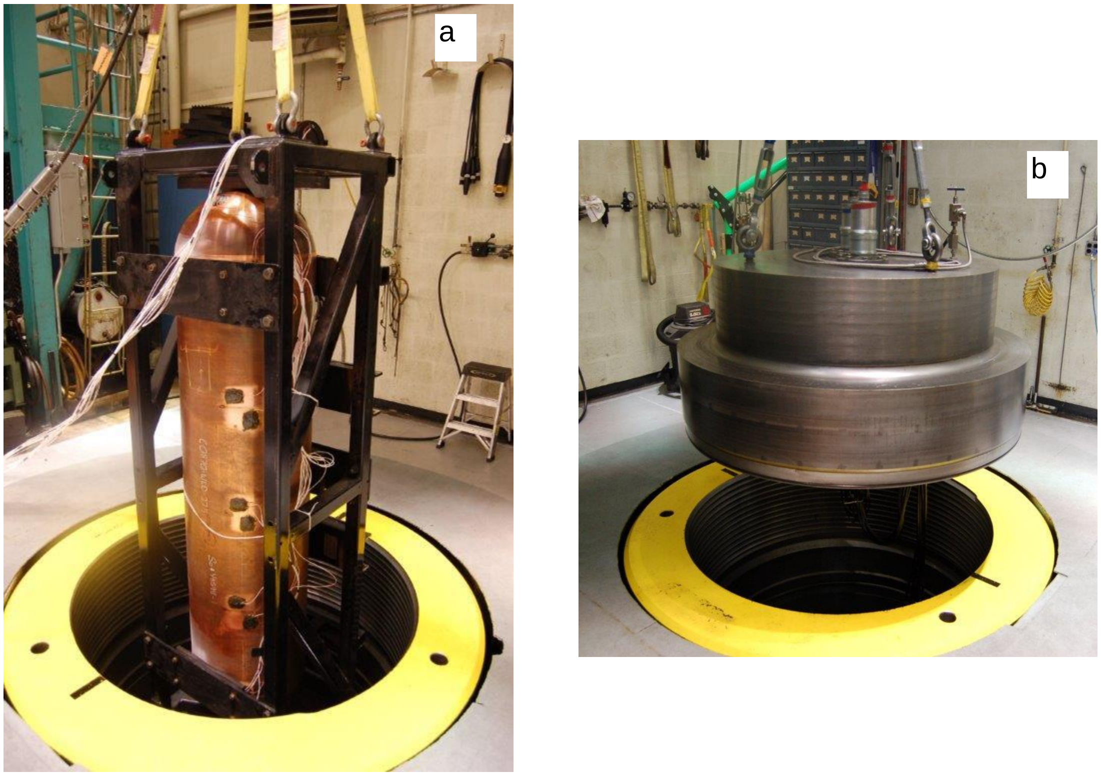


Figure 3-16: Copper Coated UFC Being Lowered into the External Pressure Test Vessel (a) at Penn State and Pressure Test Vessel Lid Applied (b)

The UFC was pressure tested under three loading conditions.

1. The first stage of testing was a monotonic pressure increase to ~15MPa (test target of 2250psi or 15.5MPa). This pressure represents the conservative maximum load that would occur in the repository due to the hydrostatic head and the buffer swelling pressure. This pressure was held for 20 minutes and then reduced back to ambient. The container was then removed from the test vessel and inspected both visually and by liquid penetrant non-destructive examination. No defects were observed.
2. The second stage of testing was a monotonic pressure increased to 45MPa (test target of 6650psi or 45.2MPa). This pressure represents the conservative maximum load that would occur in the repository due to the hydrostatic head of both the repository depth and a 3000m thick glacier, as well as the additive effect of the buffer swelling pressure. This pressure was held for 20 minutes and then reduced back to ambient. The container was then removed from the test vessel and inspected both visually and by liquid penetrant non-destructive examination. No defects were observed.
3. The third and final stage of testing proceeded by first pressurizing the copper coated UFC to ~6550psi (45.2MPa) and holding for five minutes. The pressure was then increased to 7000psi (~48MPa), which was held for 5 minutes, and then another increase to 7500psi (~52MPa), again held for 5 minutes. Pressure was then increased at a slow rate (~25psi/minute) from 7500psi (~54MPa) until failure at 7890psi (~54.5 MPa). Failure was noted by a rapid decrease in pressure of ~100psi. Upon removal from the test vessel, the UFC displayed a slight oval shape along the shell section, consistent with buckling, but no breach of the UFC was observed. Post-test liquid

penetrant examination of weld regions revealed that the containment boundary was still intact.

The copper coated UFC failed at 54.4MPa, which is in the range of the predicted collapse load from the computer modelling performed on the steel UFC (copper coating is not expected to provide any structural rigidity). The copper-coated UFC was able to withstand the maximum theoretical pressure (45MPa) that could be exerted on the container under a predicted worst-case scenario during the next glaciation. This testing demonstrated the durability of the design and the suitability of the fabrication process, including material selection, machining, welding, and copper coating techniques.

3.2.4 Used Fuel Container Corrosion Studies

Over the past several years, the NWMO has invested heavily into research programs that investigate the possible corrosion processes that may affect used fuel containers (UFCs) in a deep geological repository (DGR). This extensive program considers a wide range of scenarios, and has been developed to further the understanding of the relevant DGR chemistry in order to increase confidence in the predicted corrosion performance of the UFC. Parallel to this goal, the NWMO conducted an external peer review workshop with recognized experts in the field of corrosion. The purpose of this external peer review was to assemble an international group, consisting of 3 experts, to: 1) evaluate the current data and 2) determine the suitability of the NWMO Proof Test Plan to validate the NWMOs copper corrosion allowance. Such activities are important to demonstrate an appropriate understanding of UFC copper corrosion, in order to develop an acceptable safety case in the future for both the CNSC and the Canadian public. A summary of recommendations is provided in the peer review report for the copper corrosion program (see Section 3.2.4.3).

3.2.4.1 Radiolysis-Assisted Localized Stress and Crevice Corrosion of Carbon Steel Inside a Used Fuel Container

The current Canadian design for a UFC consists of an inner vessel of carbon steel (CS), which provides the structural strength to withstand repository loads, and an outer layer of copper acting as an external corrosion barrier. Uniform internal corrosion of a container is not a concern due to limited quantities of gas and liquid in the sealed container that could participate in this corrosion. However, gamma-radiolysis of humid air produces NO_x and HNO_3 and these species could accelerate the formation and condensation of water droplets on small surface areas to cause localized corrosion, or in crevices (which might have surface roughness features that act as preferential condensation sites). The chemical environment in acidic condensed water, coupled with the presence of radiolytic water decomposition species, could be aggressive. If water droplets condense within the crevice between the head and the body of the waste container assembly, or in the stressed regions near the welds, the corrosion in these areas could lead to a localized build-up of corrosion products (oxide deposits and H_2 gas) or stress corrosion phenomena. The result of such corrosion, over time, could lead to penetration and localized failure of the integrity of the waste container.

To assess this possibility, an experimental project has been designed to include corrosion tests of the weld regions under irradiated conditions (see Figure 3-17). In the weld region of a UFC there will be two different corrosion environments associated with 1) the crevice at the weld and 2) the adjoining boldly exposed metal surfaces. This work explores the possibility of galvanically-coupled corrosion between the crevice and bold CS surfaces in the presence of gamma-radiation. A range of gas, solution and surface analysis techniques were used to determine the extent of corrosion and the influence of gamma-irradiation. The combination of these analyses as a function of corrosion exposure or irradiation time indicated that the crevice region remains intact and that deposition of corrosion products within the crevice region does not occur. Therefore, the accelerated crevice corrosion is not anticipated to occur for a welded carbon steel container under long-term nuclear waste storage conditions.

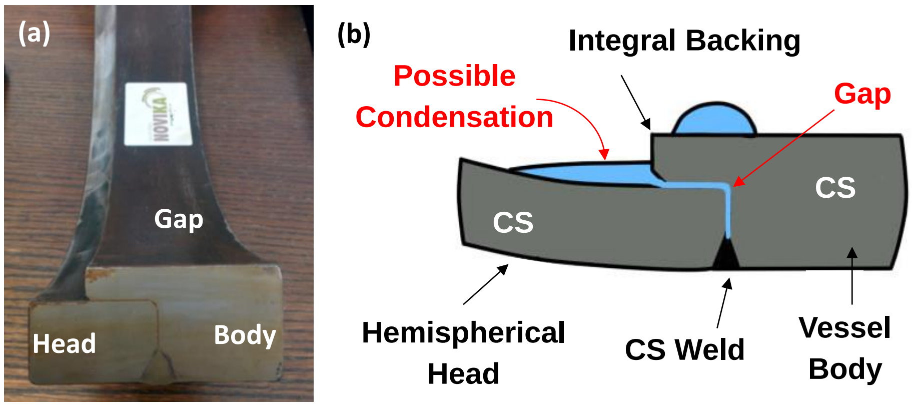


Figure 3-17: (a) Photograph and (b) Schematic of the Cross-section of the Hemispherical Head and Vessel Body Weld Region of the Canadian UFC

3.2.4.2 Damaged Coatings and Galvanic Corrosion

Although inspection procedures should prevent it, a through-coating defect in the copper layer could lead to a catastrophic container failure. In the short term, while DGR conditions are oxidizing (due to trapped O_2 and/or the γ-radiolytic production of oxidants near the container surface), the presence of a defect will render the container susceptible to galvanic corrosion. In this scenario, oxidant reduction is expected to occur on the coating surface and on the coating defect wall, thereby supporting steel corrosion at the base of the defect.

A series of additional experiments were performed in which defective coatings were simulated in inert resin layers on steel substrates by drilling through the coatings to expose the underlying steel. These electrodes were coupled through zero resistance ammeters to copper electrodes of known dimensions, and the rate of the galvanic process monitored by measuring the coupled current. A range of electrochemical, spectroscopic and microscopic techniques were used to characterize the evolution of conditions within the defect, and X-ray tomography was used to directly observe the extent and distribution of corrosion damage at the defect location. These experiments enable the accumulation of relevant kinetic information and the specification of how the relative cathode/anode areas influence the rate of steel corrosion. The goals of this project were to:

1. Evaluate quantitatively the extent and distribution of corrosion damage as a function of the inventory of available oxidant anticipated within a repository.
2. Determine what the long-term consequences of such a defect will be once anoxic conditions are eventually established.

3. Determine whether the coating process influences the distribution of corrosion damage, in particular whether or not the copper/steel interface is susceptible to corrosion and possible debonding.
4. Accumulate a quantitative database that will enable specification of the chemical conditions prevailing within a corroding defect, and use them to develop a model to predict the long-term corrosion rate.
5. Use the direct observations from X-ray tomography as the basis for the evaluation of corrosion damage and for validation of the corrosion model.

Based on chemical surface analysis and electrochemical measurements, the chemical and electrochemical processes within a simulated defect have been determined for O_2-rich solutions and are summarized in Figure 3-18.

X-ray micro-tomography measurements show void spaces within the coating, produced during coating development. These voids are a result of the cold spray process and are expected to be absent in coatings produced following an optimization process. Because they will not exist in the container, they are not included in the corrosion allowance. Looking at the copper/steel interface following 42 hours immersion (Figure 3-19b), corrosion products are uniformly distributed on the exposed steel surface, indicating a minimal microstructural influence on the corrosion front and, at least within this exposure timescale, no localized corrosion. Figure 3-19 also indicates that the corrosion process propagates along this interface and overcomes the bonding strength between the coating and the steel. Again, it is essential to note that the cold-spray coating process was far from optimized on this particular specimen. Additional studies show that the interface on electrodeposited coatings does not experience a similar corrosion process.

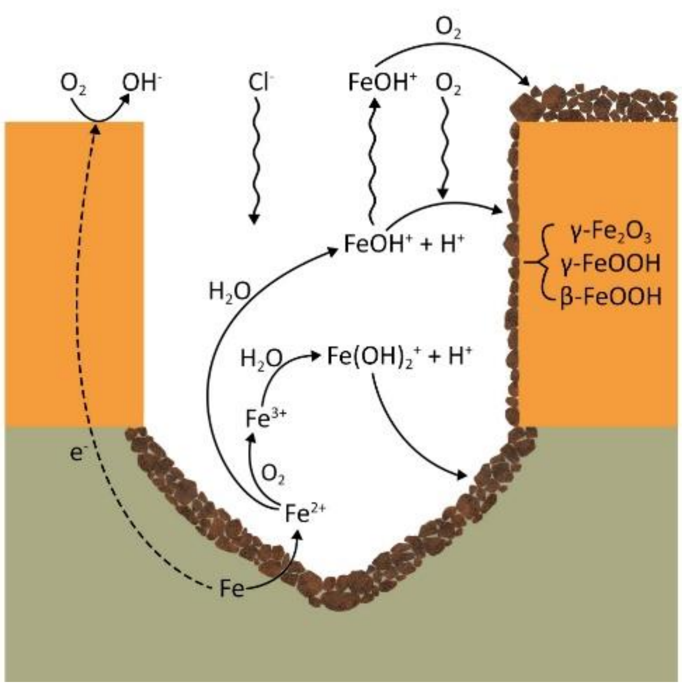


Figure 3-18: Schematic Illustration of the Chemistry Inside a Coating Defect during Corrosion in an O_2-purged 3 mol L^{-1} NaCl Solution

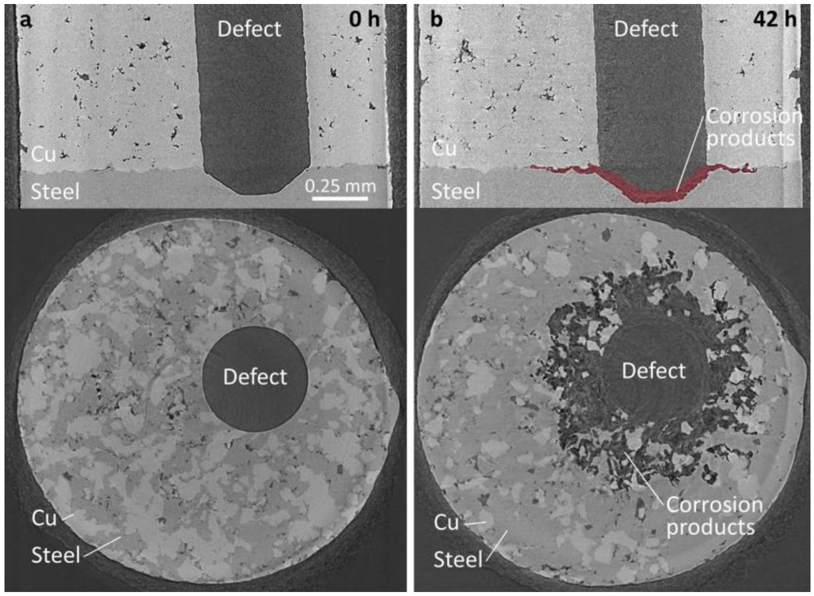


Figure 3-19: Synchrotron Micro-CT Vertical and Horizontal Image Slices of the Cold Spray Cu/steel Interface after Exposure to O2-sparged 3 mol L^{-1} NaCl Solution for 0 Hours (a) and 42 Hours (b). The Accumulated Corrosion Products are Highlighted in the 42 Hours Vertical Image Slice

3.2.4.3 Peer Review Report of Copper Corrosion Program

The peer review was conducted through a 2-day working session at the NWMO offices in Toronto, Canada. The review consisted of presentations by NWMO researchers detailing the elements of the Proof Test Plan related to copper corrosion. The review panel concluded that through a combination of academic institutions, industrial consultants, and international collaborations, the NWMO has developed a well-integrated and world-leading research team to conduct this work. A summary of review comments, recommendations and responses by the NWMO with respect to future work are summarized below.

- <u>Anoxic Copper Corrosion</u>

  The review committee advised that anoxic copper corrosion investigations should emphasize efforts for identifying the source and technical basis for hydrogen observed during experiments in pure water and brine. The effect of sulphide as a potential catalyst for anoxic copper corrosion should be specifically assessed. In response to these recommendations, the corrosion program is continuing work within its on-going anoxic corrosion programs and has begun a detailed investigation on the source of hydrogen in copper. In addition, the NWMO will include work in low-sulphide concentrations to investigate the potential for sulphide to act as a catalyst for the corrosion of copper.

- <u>Copper Coating</u>

  The review emphasized a focus on continuing to characterize samples that use the proposed coating processes (electrodeposited and cold sprayed copper instead of wrought) and to evaluate their resultant corrosion behaviour directly. The technical basis for any differences in corrosion behavior between electrodeposited copper, cold sprayed copper and wrought copper should be understood; this includes sulphide-induced corrosion, radiolytic corrosion, and anoxic modes (i.e., any that contribute to the corrosion allowance calculation). The NWMO will continue its on-going programs comparing the corrosion behaviour of wrought and coated copper. The scope will expand to explore additional corrosion scenarios, including those suggested by the review committee.

- Localized Corrosion

  With respect to localized corrosion on copper, the committee suggested that the research should continue to define differences between active and passive conditions to ensure that corrosion via pitting does not occur. Long-term testing is encouraged. In response to these suggestions, the NWMO is planning to initiate a new joint program with the Swedish Nuclear Fuel and Waste Management Co. (SKB) in early 2017. The scope of this new program will include the collection and analysis of statistical data from multi-electrode array experiments.

- Stress Corrosion Cracking

  The committee recommended that, should design elements change or environmental conditions differ from those currently expected, the NWMO continue research into the potential for stress corrosion cracking to occur. The NWMO will continue to re-assess its assumptions regarding stress corrosion cracking as design changes are implemented and/or as additional site-specific information is available.

- Future Studies Recommendation

  The review states that future studies should consider the potential for hydrogen blistering and coating delamination, either from radiation-induced absorption of hydrogen into the copper coating corrosion products at the copper/steel interface, or from hydrogen produced during internal container corrosion of the steel structural element. The NWMO is initiating a new program to examine the movement of hydrogen in copper and steel to determine the potential effects at the copper-steel interface.

4. GEOSCIENCE

The NWMO is pursuing a multi-disciplinary applied geoscience technical program, which includes collaboration with Canadian and international specialists and Universities, that is focused on preserving site characterisation and interpretative methods in deep seated crystalline and sedimentary rock environs necessary to assess geosphere stability and long-term barrier integrity relevant to the safe implementation of the APM repository concept.

4.1 GEOSPHERE CHARACTERIZATION

4.1.1 Hydrogeochemistry

In 2016, the NWMO continued to support work programs, with researchers in Canada and abroad, focused on the development, refinement and testing of methods to enhance porewater extraction and characterization from low-permeability rock formations. The research programs aim to develop and refine isotopic and geochemical analysis techniques that can be used in site investigation activities in both sedimentary and crystalline rock, as chemical and isotopic compositions of groundwater, matrix porewater and rock provide information on the evolution of the overall system and can be used to determine fluid and solute fate over geologic time frames.

The work undertaken at the various universities and research institutes, summarized herein, is detailed and rigorous, with emphasis placed on the ability to accurately and reliably analyze rock material, to extract and analyze porewater and gases, to infer relative ages and timing for fluid/secondary mineral emplacement, and to characterize solute transport, in order allow for high-confidence interpretations of deep groundwater system evolution and stability. The work programs summarized here highlight the value of the research and expertise provided by both Canadian and international researchers to the NWMO, in the context of advancing the Canadian nuclear waste management program and ensuring the application of best scientific practice in all aspects of geochemical characterizaton activities.

4.1.1.1 Porewater Chemistry and Isotopes

Porewater chemical and isotopic properties are some of the most important data that contribute to a comprehensive understanding of the origin, evolution and residence time of fluids deep in the geosphere. As such, they are critical to understanding the long-term stability of the groundwater system. Research undertaken at various universities has focused on enhancing abilities to measure porewater chemistry and stable water isotope composition. These research activities are directed toward low-permeability crystalline and sedimentary rock, with the objective of improving the understanding of deep groundwater system origin, evolution and long-term behaviour, as relevant to demonstrating suitability and safety on repository-relevant timeframes. In 2016, work in these subject areas was extensive and highlights from the work programs are summarized below.

University of Ottawa

Work continued at the University of Ottawa on a novel method that aims to absorb porewater from the rocks into cellulosic papers. The method has been under development for several years, first at the University of New Brunswick and continuing at the University of Ottawa.

Recent work on this technique has focused on the prevention of artefacts from: i) evaporation during sample processing, and ii) the adherence of particulate material from the rock cores to the cellulosic papers. These artefacts have been substantially reduced by the construction of a humidity chamber for sample preparation that reduces evaporation rates to negligible levels, and by the use of protective membranes that lay between the rock core surface and the cellulosic paper. The completion of trial extraction and analyses on core samples using these new approaches were undertaken in 2015-2016. Work on this method with rocks from the Michigan Basin and Switzerland suggests that the cellulosic paper is selective for the mobile fraction of porewater only (exclusive of bound water and water occupying interlayer positions in clays).

The analysis of porewater isotopes in crystalline rock represents a further challenge that is being addressed in the current research program. Porewater extraction and analysis from crystalline rocks presents unique difficulties because of the low porosity (low water content) and the presence of saline fluid inclusions that negate the use of crush and leach techniques. The method involves elevated-temperature extraction under closed-system vacuum conditions using intact core sections. Water extraction and trapping for stable isotope analysis is being tested using a modified vacuum distillation line with a stainless steel canister that holds an intact core, up to 85 mm diameter. A conflat copper gasket with knife-edge seal allows maintenance of a high vacuum for relatively long time periods at elevated temperature. Tests to-date show that core lengths as short as 10 to 15 cm can be successfully used. Work to be undertaken in 2017 and beyond includes evaluations of yield and stable isotope measurements for various times and temperatures, using cores pre-conditioned with water of known composition, in order to establish a routine protocol for the extraction of crystalline porewaters, as will be necessary for APM siting activities.

The use of magnesium, calcium and lithium isotopes are being examined using cores from the low- and intermediate-level waste DGR program at the Bruce nuclear site for insights on the origins of salinity. To-date, work has progressed on magnesium and lithium isotopes. The Upper Ordovician carbonate rocks in southwestern Ontario contain post-dolomitic brines that are believed to have residence times exceeding 260 Ma, and magnesium isotopes are an emerging tool in the study of dolomite formation, magnesium cycling, and past continental weathering fluxes. Detailed vertical profiles for δ^{25}Mg and δ^{26}Mg of porewaters and groundwaters at the site are being completed to provide insights into the mechanism of brine emplacement. These data, when combined with the lithium and calcium isotopes, will help to further constrain solute migration and the relative age of porewaters. Lithium concentrations in the sedimentary rock at the Bruce site are elevated far above seawater concentrations, with values in the range of 10 ppm. The capability to prepare samples, using column extractions, for isotope analysis on the NU multi-collector ICP-MS at the Geological Survey of Canada, was developed and tested in 2015, and preliminary lithium isotope data was collected in 2016.

The isotopic analysis of heavy noble gases in preserved cores (in porewaters) is a newly initiated project to complement helium isotope studies that were performed as part of the development of the geosphere model for the Bruce nuclear site. In this new work, the Helix multi-collector noble gas mass spectrometer is being interfaced with a new noble gas purification and separation line at the University of Ottawa, to allow the simultaneous analysis of ^{36}Ar/^{40}Ar and ^{136}Xe/^{128}Xe. Ingrowth of these isotopes above their atmospheric ratios will provide robust chronologies of the porewaters in this system to complement the He, CH_4, and ^{87}Sr and chronometers that have already been developed. The strontium research was completed and the manuscript on this work is nearing completion for submission to the Canadian Journal of Earth Sciences.

University of Bern

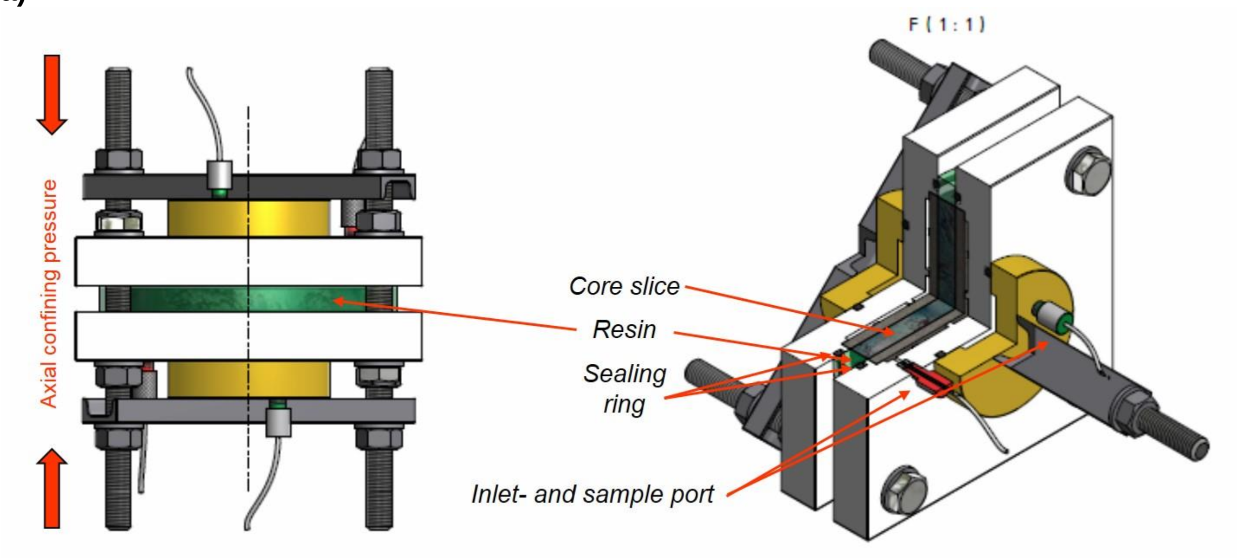
The work at the University of Bern aims to expand the applications/capabilities of specific techniques (e.g., isotope diffusive exchange, squeezing) that have been applied in various European nuclear waste management programs, to the applicable rock types of significance in the Canadian nuclear waste management program (i.e., high salinity, low porosity and low permeability sedimentary and/or crystalline rocks).

In 2016, work continued to develop and initiate a benchmarking exercise to assess results from both isotope diffusive exchange and squeezing on sedimentary rock. The isotope diffusive exchange technique was specifically adapted over the course of characterization activities at the Bruce nuclear site to allow for successful analysis of high-salinity Ca-rich (Ca-Na-Cl) brines, which are frequently encountered in sedimentary rocks of the Michigan Basin in southwestern Ontario (see de Haller et al. 2016). Further refinement of the method, in 2015 and 2016, aims to allow the analysis of small sample volumes from low water content rocks, typical of those encountered in Canadian Shield and sedimentary environments. With the advent of the Cavity Ring-Down Spectroscopy (CRDS) method to analyze stable water isotopes, the analysis can be made with very small masses of water. The next step in optimization of the adapted isotope diffusive exchange technique is focused on this concept (i.e., reduction of the mass of test water required for analysis), which is expected to extend the range of applicability of the method to rocks with relatively low water contents (ca. 2% or less). The results of the isotope diffusive exchange component of the benchmarking experiment (described below), when completed, will be compared with those obtained from the porewater squeezing component, a method which was demonstrated in 2013 to be applicable to Paleozoic rocks of southwestern Ontario (see Mazurek et al. 2013). The key objective with respect to the squeezing technique is to assess its applicability in the context of deep-seated Canadian sedimentary host-rock environments, in which formation permeabilities are typically low and porewater extraction techniques are laborious, as well as to assess the magnitude and nature of analytical artefacts (e.g., mineral dissolution, ion filtration) associated with the high-pressure extraction of porewater. Over the course of 2015 and 2016, it was observed that the sample geometry can, indeed, have an impact on the volume of water extracted from low-porosity rock materials during squeezing, as the pressures required to extract water for analysis can be quite high (up to 500 MPa), which is a key finding that is of relevance to the benchmarking work, as well as to any future sampling campaigns in which squeezing will be included as a component of the porewater extraction and characterization plan.

For the benchmarking experiment, which includes shale samples from Canada and Switzerland, detailed and rigorous work was undertaken in 2016 to develop sample containers that would allow for sample saturation while restricting the ability of the enclosed samples to swell. This was successfully achieved in 2016 and samples are currently undergoing saturation with test waters of known chemical and isotopic composition (see Figure 4-1).

After full chemical and isotopic equilibration, paired core pieces will then be subject to either squeezing or isotope diffusive exchange experiments following standard protocols. The analytical results will be compared with the known composition of the test water used, which serves as a benchmark. The saturation component of the experiment will be complete early in 2017, which will be followed by these porewater extraction, analysis and comparison activities. When complete, this work will allow for determinations to be made about the magnitude of artefacts (chemical and isotopic) related to the extraction of porewaters at high pressures (e.g., 50-500 MPa) from sedimentary rock cores in a confined system, as well as any potential artefacts associated with isotope diffusive exchange. Because these methods are anticipated to be of importance in APM siting activities for the geochemical characterization of porewaters, understanding the applications, limitations and potential artefacts of these methods are of relevance to planning activities.

a)



b)

Figure 4-1: a) Schematic of Confining Cell for Saturation Component of the Benchmarking Experiment; Fluid of Known Composition is Injected at the Inlet. b) Experimental Set-up – Edges of the Core Discs are Sealed in Resin, in Addition to the Presence of Sealing Rings – Maintains Closed-system Conditions during Saturation

Western University (University of Western Ontario)

The reliable measurement of stable water isotopes in the porewaters of the Paleozoic formations at the Bruce nuclear site presents a challenge due to the very low water content and the presence of clays. A concern that is being examined in the current research, which is in collaboration with the University of Ottawa, is the potential for bias of the vacuum-distillation method due to fractionation between connected-porosity water and clay hydration water.

In 2016, a work program was initiated at the University of Western Ontario to investigate the potential for different porewater extraction techniques to sample water from different reservoirs within clay-rich rocks. This is highly relevant for the APM program, as differences in measured isotopic compositions between methods must be qualified in order to demonstrate understanding of the techniques employed and to ensure confidence in the geochemical interpretation in the scientific community. Measurement of porewater hydrogen (δ^2H) and oxygen (δ^{18}O) isotopic compositions is a key component of any geochemical characterization program for a potential long-term deep geologic repository for radioactive waste. This is the case because these isotopes can provide quantitative insight into the potential for migration of radionuclides from source, and in particular, clarify the roles that diffusion and advection have played in determining the current isotopic composition(s) of the porewater(s). Isotopic information is used to assess mixing relationships, groundwater/porewater origin and evolution, as well as water-rock interaction processes. Accordingly, accurate and reproducible isotopic data for porewater from low-permeability rocks is an essential part of the safety case for proposed repositories in the context of establishing a case for long-term geosphere stability and solute residence times.

This research will investigate if the observed differences between vacuum distillation and isotope diffusive exchange can be attributed to analytical artefacts associated with the release of bound and interlayer waters in clays as a result of the thermal extraction process. The work will involve the collection of water released from clay minerals under controlled heating (under vacuum), using a Differential Thermal Analysis (DTA)-Thermogravimetric Analysis (TGA) balance. The work will involve the determination of the oxygen and hydrogen isotopic fractionation between porewater and interlayer water for a range of clay minerals. Special emphasis will be placed on characterizing the isotopic differences between surface adsorbed water and mobile water in the pore system. The overall objective is to use combined thermogravimetric and stable isotopic analysis to evaluate the role that the release of clay-bound hydration waters may play in the determination of measured stable water isotope compositions when porewaters are extracted via the vacuum distillation method at 150^{o}C (as developed and adapted at the University of Ottawa). The work program involves development of the apparatus required to collect the water (vapour) samples during each heating step, and focuses primarily on the measurement of the oxygen and hydrogen isotopic compositions of various ‘waters’ associated with a range of clay minerals (i.e., those that contain interlayer water and those that do not).

Laboratory analyses have not yet begun, but test samples (preserved shale samples from the Bruce nuclear site) have been provided for development of the technique (i.e., to assess if it will be successful on the shale materials that typify southern Ontario). Work to-date has focused on the establishement of the TGA – *in vacuo* water collection system at the University of Western Ontario. Once the system is fully tested and verified, a series of experiments on various clay/shale samples will begin in 2017.

University of Waterloo

In 2014, groundwater samples from three zones of two deep boreholes, DGR-3 and DGR-4, at the Bruce nuclear site were analyzed for stable isotopes of Cl and Br, in conjunction with their geochemical parameters, to ascertain the origin of salts and the fluids containing these elements. The groundwaters were collected from two Silurian-aged units, the Salina A1 carbonate and Guelph formation, and the Cambrian sandstone unit (Wang and Frape 2015). Study results reveal that the sampled groundwaters have isotopic and geochemical signatures similar to formation fluids from the same geological units elsewhere in southern Ontario. The Salina A1 groundwater samples have very low Br/Cl weight ratios and depleted δ^{81}Br and δ^{18}O isotopic signatures. The Salina A1 groundwater samples appear to have been derived from halite dissolution and impacted by cold climate recharge, having a depleted δ^{18}O and δ^{2}H isotopic values (Clark et al. 2013; Al et al. 2015). The Guelph Formation groundwater samples are isotopically depleted in δ^{81}Br and δ^{37}Cl. The d^{81}Br and δ^{37}Cl isotopic compositions, and the Cl/Br ratios, determined for groundwaters from the Silurian Salina A1 and the Guelph formations are consistent with other regional groundwaters that are described as having been sourced within the Michigan Basin, with fluids depleted in δ^{81}Br (Wang and Frape 2015; Skuce et al. 2015; Hobbs et al. 2011). The Cambrian groundwaters show enriched δ^{81}Br and δ^{37}Cl isotopic signatures, similar to those found elsewhere in the Cambrian as it occurs in the Appalachian Basin to the east and south, which suggests a similar origin for the fluids (Wang and Frape 2015). The halide isotopic signatures of the Cambrian groundwaters suggest that these fluids are very old, as their isotopic compositions have been maintained since emplacement during regional basin-scale fluid movement events occurring in the Paleozoic (see Ziegler and Longstaffe 2000a, 2000b; Bailey 2005).

Phase II work in 2015 and 2016 focused on determination of the Cl and Br isotopic ratios for porewaters (in the form of leachates from 2-4 mm grain-size rock particles (Figure 4-2 and Figure 4-3). This work was completed in the Fall of 2016 and will be summarized, along with the groundwater results, in a technical report for the NWMO in 2017. This work, when combined, will provide additional insights about the origin and longevity of fluids in the sedimentary sequence at the site.

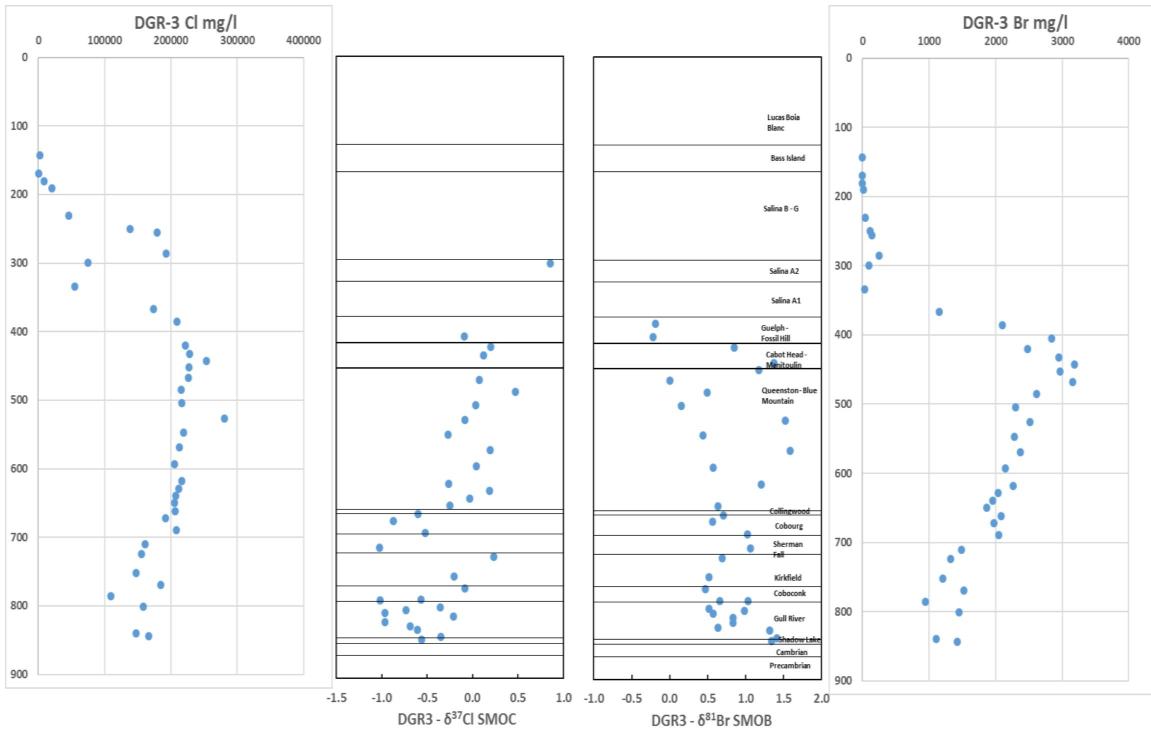


Figure 4-2: Cl and Br Concentrations and Isotopes ($\delta^{37}Cl$, $\delta^{81}Br$) for Porewaters from DGR-3

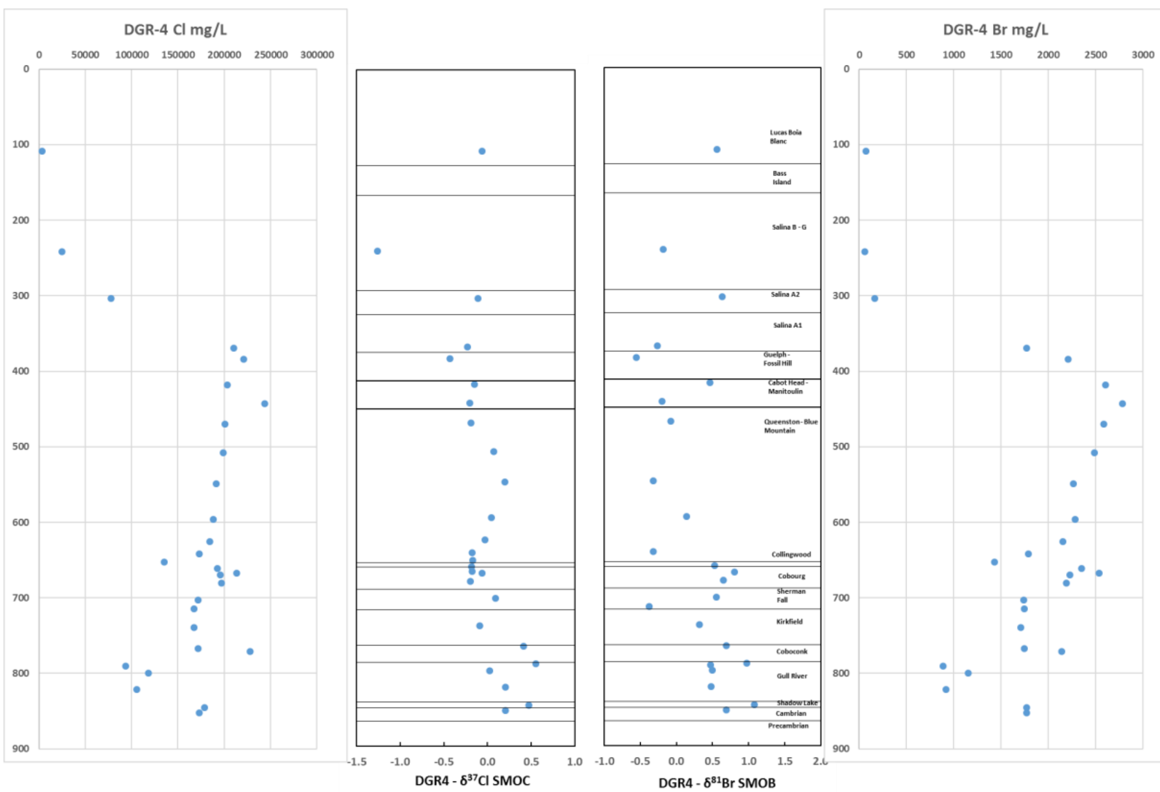


Figure 4-3: Cl and Br Concentrations and Isotopes ($\delta^{37}Cl$, $\delta^{81}Br$) for Porewaters from DGR-4

4.1.1.2 Mont Terri: Deep Borehole (DB) and Porewater Characterization (DB-A)

The goal of the Deep Borehole (DB) experiment at the Mont Terri Underground Rock Laboratory was to develop and validate a methodology for assessing the contaminant transport properties of a thick argillaceous formation using the Opalinus Clay as an analogue, which involved investigating the processes and properties that define the Opalinus Clay as a confining unit. In order to facilitate this investigation, pressure, temperature, and chemical gradients were measured regularly across a 250 m borehole (drilled in 2012 and equipped with a 7-interval multipacker system) that includes the Opalinus Clay, as well as the over- and underlying aquifer formations. As of 2016, the DB Experiment remains in the modelling and data interpretation phase.

The DB Experiment provided an opportunity to design a complementary benchmarking and aquifer interface characterization experiment (DB-A). DB-A provided an opportunity to benchmark existing methods used internationally, as well as methods developed as part of the L&ILW DGR and APM programs at the NWMO. DB-A included researchers from the University of Ottawa, the University of New Brunswick and the University of Bern (including the CRIEPI and CIEMAT laboratories in Japan and Spain, respectively). Benchmarking activities were completed by mid-2015 and included the micro vacuum-distillation, isotope diffusive exchange and squeezing methods for stable water isotopes, and the filter paper, aqueous extraction, squeezing and crush-and-leach techniques for major ion chemistry. In addition, noble gas analyses performed at the University of Ottawa and the University of Bern allowed comparison of two slightly different core encapsulation and analysis techniques for helium. Core samples for the analyses were collected immediately and adjacent to one another during drilling (initiations of the DB experiment), and were preserved on-site by staff from NAGRA, the University of Bern and the University of Ottawa early in 2014. This collaborative experiment allowed a direct comparison of results derived from the methods indicated above, as well as assessments of method applicability and potential analytical artefacts. The results of this experiment led to the collaborative work currently being undertaken at the University of Ottawa and the University of Western Ontario (as previously described in Section 4.1.1.1). One of two technical reports documenting the results of the DB-A experiment, the method benchmarking exercise, was completed in 2016. A second report detailing the results of the aquifer interface investigation is expected in 2017. Both of these reports will be submitted to the Mont Terri Consortium for publication in 2017.

4.1.1.3 Redox Processes

Previous studies of the concentrations and isotopic properties of CH_4 and CO_2 in sedimentary cores from the Bruce nuclear site indicate that biological and thermochemical processes are responsible for the formation of gases present at various depths in the Upper Ordovician section. The data suggest that the biogenic CH_4 is ancient, predating the emplacement of the Late Silurian brines, and has been essentially immobile since that time. Isotope enrichment in components of residual organic substrates also can be diagnostic of their origin and degradational history. As biodegradation of primary sedimentary organics, including n-alkanes and PAHs, induce different carbon isotopic fractionations, compound-specific isotope analysis (CSIA) on these molecules has the potential to shed light on microbial dynamics in a given environment. As a result, work undertaken at the University of Ottawa involves evaluating the organic carbon substrate for evidence of isotopic enrichments that correlate with the methane and biogenic CO_2 signatures in the Ordovician sediments. To-date, rock crushing has been carried out at the University of Ottawa under anaerobic conditions to avoid oxidation of dissolved organic matter and sulphide phases. Organic fractions have been extracted with organic solvents and analysed for composition using facilities at the Delta-lab GSC-Québec. CSIA was initiated in 2016 at the Institut Nationale de la Recherche Scientifique (INRS), and the work is on-going. The results are to be integrated later into a model for the evolution of redox conditions in the Ordovician shales and argillaceous limestones.

A new approach to characterize organic matter in the Ordovician sediments involves collaboration with the Photonics research group in the Advanced Research Complex at the University of Ottawa. A high-resolution laser technique, based on Raman scattering, is being developed for analysis of organic carbon in rock samples (Coherent Anti-Stokes Raman Spectroscopy, CARS), using archived Ordovician shale material. The work is anticipated to begin in 2017 and is designed to provide a micrometer scale measurement of biodegradation to complement the CSIA measurements described above.

The sulphur system is the focus of another project at the University of Ottawa using ^{34}S and ^{18}O in sulphate, together with ^{34}S in reduced sulphur phases including organics, framboidal pyrite, and other iron-bearing phases, with the aim of linking the influx of sulphate during Silurian salinization/dolomitization with framboidal pyrite formation through microbial activity by sulphate reducers. Progress to-date includes development of the extraction and analytical methodology for isotopic analysis of porewater sulphate. In addition, a new method using divalent chromium was developed at the University of Ottawa for the extraction of H_2S from sulphide-minerals in the Ordovician sediment and trapping the sulphur as AgS. Along with data from organic carbon and secondary carbonate, the sulphur data will be synthesized into the conceptual model that is being constructed to understand redox evolution and stability.

4.1.1.4 Dolomitization

A research agreement undertaken with the University of Windsor in 2015 investigated the nature and origin of strata-bound near-horizontally layered dolomitized beds occurring within the bedrock formations of the Black River Group in the Huron Domain of southern Ontario. Dolomitization occurs when limestone ($CaCO_3$) is progressively changed to dolomite ($MgCO_3$). Dolomitization can occur due to a broad range of geologic and geochemical process including: a) sabkha-type, b) mixed-water aquifer, c) seepage reflux, d) burial compaction, and e) hydrothermal. A technical report published in 2016 (NWMO TR-2016-05) describes the results of this initial study. Evidence indicates that Cambrian and Ordovician formations were subjected to higher temperatures than can be explained by burial history alone.

Dolomite and calcite fracture infill isotopic and fluid inclusion data point to two possibly isolated diagenetic fluid systems: i) an earlier Cambrian system that is characterized by a more radiogenic, cooler and saline signature; and ii) a later Ordovician system that is characterized by hypersaline, more hydrothermal and a less radiogenic fluid system (see Figure 4-4). The observation of highly discrete, strata-bound dolomites combined with only trace quantities of saddle dolomite, and its associated geochemical signature, suggest that diagenesis, as a result of hydrothermal fluids, was restricted to these horizons in the Ordovician and was pervasive neither in volume nor extent at the Bruce nuclear site. In the Cambrian, the distribution and volume of diagenetically-altered material suggests that dolomitization was more widespread (albeit with lower temperatures) due to the higher porosity and permeability of the Cambrian sandstones.

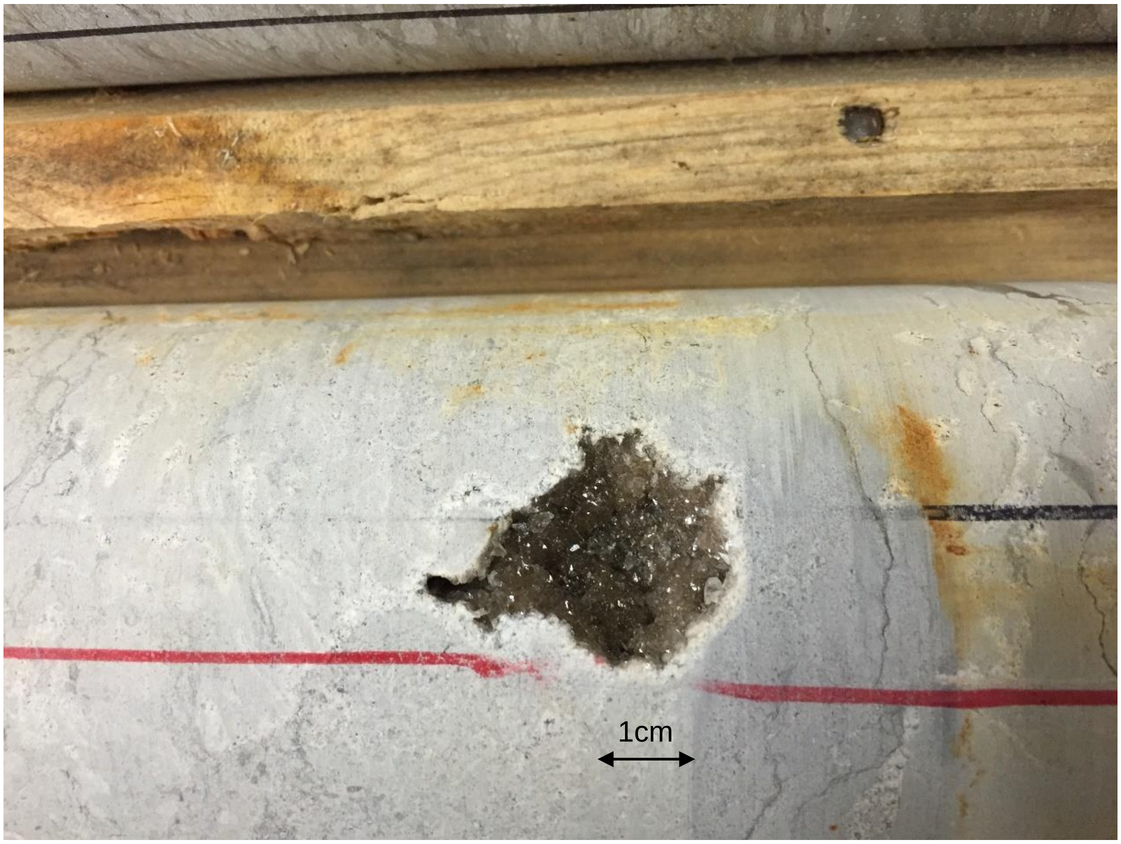


Figure 4-4: Well Core from the Ordovician Gull River Formation in DGR-6 (Bruce site) Selected for Sampling. Large Vug is Ringed with Dolomite (white) and Contains Large Calcite Crystals (grey). Both of These Minerals are the Product of Paleozoic Hydrothermal Fluids

A new contract was signed with the University of Windsor in 2016 to expand and extend the work program for a further 2 years. The scope of the program was broadened, with a new and significantly larger sampling program. This involved 12 additional samples taken from Ordovician and Cambrian well cores at the Bruce nuclear site and 44 samples from the same formations in 5 regional wells within the Huron Domain, at distances of up to 100 km from the site. These well core samples were taken from storage at the Ontario Gas, Salt Rock Library (OGSRL) in London Ontario and were sent to the University of Windsor for isotopic analysis and fluid inclusion microthermometry. Results from this new phase of the study are expected in the latter half of 2017.

4.1.2 Subsurface Mass Transport

Near-field performance, safety assessment and groundwater transport/evolution models require knowledge of groundwater and porewater geochemical compositions, as well as petrophysical and solute transport properties, in order to provide representative estimations of long-term system behaviour. The following work programs contribute significantly to the NWMO's technical capabilities in the context of assessing long-term solute mobility and retention.

4.1.2.1 Diffusion

In 2016, multiple studies focused on various aspects of diffusion in low-porosity rock (i.e., limestone, crystalline). The University of Ottawa acquired a new X-ray CT system in September of 2016, and, for the remainder of the year, a variety of experiments were conducted to test instrument performance and to optimize measurement parameters for tracer experiments. In 2017, experiments will begin on low-porosity rocks, with an emphasis on assessing the potential for preferential diffusive pathways in intact rock, as well as the effect of partial saturation on the effective diffusion coefficient (D_e). The diffusion experiments on partially-saturated sedimentary rock aim to measure the degree to which diffusion coefficients for aqueous solutes decrease as the fraction of gas-filled porosity increases, and this work has great potential to be scaled up to 3-D from 2-D. Additional work is focused on the determination of diffusion coefficients for dissolved gases, helium (He) and methane (CH_4). In the experiments, which involve the development of appropriate apparatus (in 2015) and comparison of through-diffusion and out-diffusion techniques, He was chosen because it behaves conservatively and can provide a benchmark for the highest diffusion rates that might be expected for gases in low-porosity rock. CH_4 is common in deep sedimentary and crystalline rocks, and its use in these experiments has the potential to provide a better understanding of CH_4 transport properties in such rocks and to provide additional evidence for the residence time of porewater and gases in deep low-porosity systems. The experimental design was completed in 2016 and through-diffusion measurements will begin in 2017. The next step in the research will involve comparison measurements on replicate samples using both through-diffusion and out-diffusion techniques, to assess which technique is best suited for use in such applications.

In 2016, a journal article was published (Xiang et al. 2016) highlighting the differences in D_e values observed when core samples are measured in the laboratory under atmospheric pressure following core relaxation, or when measured under in-situ pressures. The paper documents the results of through-diffusion experiments conducted under confining pressure on samples from the Michigan Basin in southern Ontario and from the Opalinus Clay in Switzerland. Work on these effects is expected to continue in 2017 using radiography, as core samples become available during APM drilling activities. For this work, the differences in D_e between in-situ and laboratory conditions will be evaluated by conducting measurements on paired samples from a variety of rock types: one of each pair will be confined in a pressurized diffusion cell immediately after drilling, and the other will be handled using standard methods. This work allows quantifiable estimates to be made of the effects of core relaxation on measured diffusion coefficients, which links directly to estimates (calculations and modelling) of solute longevity and solute mobility in the hydrologic system.

4.1.2.2 ANPOR

The Anion Accessibility in Low Porosity Argillaceous Rocks (ANPOR) research program was initiated in February, 2014, jointly funded by the Paul Scherrer Institute (PSI) in Switzerland and the NWMO, and will come to completion in July 2017. The research program investigated the anion exclusion effect in clay rocks using samples from Canada (Queenston and Blue Mountain shales) and Switzerland (Opalinus Clay and Helvetic Marl).

Through-diffusion experiments with tritiated water (HTO) and chloride ($^{36}Cl^-$) were performed to assess the total porosity (HTO) and the anion accessible porosity ($^{36}Cl^-$) for samples equilibrated with porewaters of different composition ranging from 0.01 M – 5 M NaCl. Even when the natural in-situ porewater had a very low (0.25 M – Swiss samples) or very high (>5 M

– Canadian samples) ionic strength, no problems were evident during sample conditioning with artificial porewater at different ionic strengths. For this work, all diffusion experiments were performed perpendicular to the bedding plane of the samples. A journal publication detailing the work on samples from Switzerland was accepted for publication in 2016 and can be found in print in the Environmental Science and Technology Journal in January 2017 (Wigger et al. 2017).

In addition to the diffusion experiments, the pore geometry, as a limiting factor for anion diffusion in clay rocks, was investigated using five different pore size distribution measurement methods: Nuclear Magnetic Resonance (NMR), NMR cryoporometry, mercury intrusion porosimetry and CO_2 adsorption, as well as N_2 adsorption. Due to different physical principals of these methods, various pore width ranges, from micropores (<2 nm) to mesopores (2-50 nm) to macropores (>50 nm), could be detected (Figure 4-5). The aim was to shed light on the role of small pores on the transport properties of natural clay rocks, in particular to provide a possible explanation for the differences in anion diffusion between the different clay rock samples from Switzerland. Knowing that the Helvetic Marl (HM) has a larger permanent anion exclusion than the Opalinus Clay (OPA), it was expected that HM will have more interlayer equivalent (ILE) pores than OPA. ILE pores are so narrow (<0.5 nm) that diffuse double layers, which form at negatively charged surfaces, are actually overlapping, such that the pores behave like interlayer pores and may inhibit/prevent anion diffusion. This investigation could not, however, confirm this assumption, particularly because the detection range is limited for such small pores.

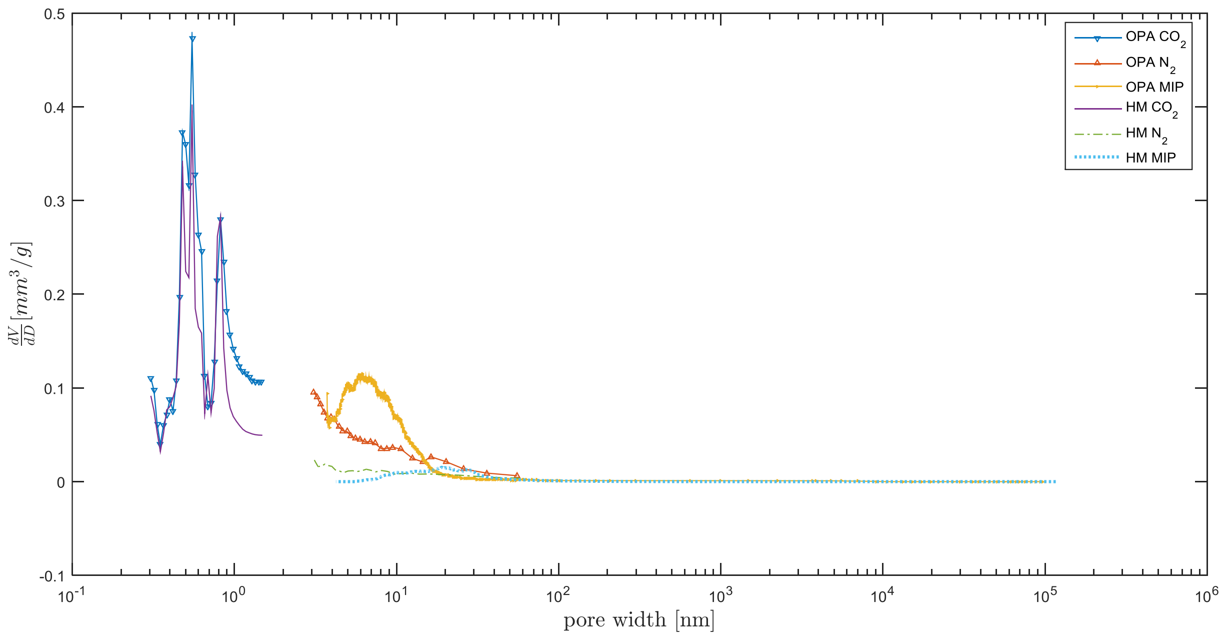


Figure 4-5: Pore Size Distributions of Opalinus Clay and Helvetic Marl Measured by CO_2- and N_2-adsorption and MIP

Work on anion diffusion through the Canadian samples (Queenston and Blue Mountain formations) was completed in August of 2016, and the results indicate that, relative to the total concentration, more anions diffuse through the samples at higher ionic strength. Data analysis on the Canadian sample using COMSOL is on-going as of December, 2016. The results are to be compiled in a PhD thesis and report for the NWMO, both of which are to be completed by July 2017. Submission of a scientific journal publication, detailing the results for the Canadian samples, is also anticipated to occur in 2017.

4.1.2.3 Sorption

Sorption is a potential mechanism for retarding sub-surface radionuclide transport from a DGR to the environment. Radionuclide sorption data is necessary for safety assessment studies of a DGR for radioactive waste. The NWMO has supported a long-term comprehensive program for the development of sorption distribution coefficient (K_d) data. The development of a Canadian sorption database for highly saline groundwaters was initiated by conducting a review of the open literature and international sorption databases – to find any data potentially relevant to Canadian sedimentary rocks (shale and limestone), as well as bentonite clay, for the elements of interest for safety assessment (results published in Vilks. 2011). This initial database has been augmented with new literature values, as well as with sorption data determined experimentally via batch and long-term diffusion tests for the elements Cu(II), Ni(II), Pb(II), Eu(III), U(VI), and Zr(IV) using Canadian sedimentary rocks and bentonite clay in saline solutions (Vilks et al. 2011; Vilks and Miller 2014).

In 2013, a two-year research program, in collaboration with Canadian Nuclear Laboratories, was initiated to further develop the NWMO's database of K_d values for Canadian sedimentary rocks and bentonite clay for these elements: C, Cl, Ca, Ni, Cu, As, Se, Zr, Nb, Mo, Tc, Pd, Ag, Cd, Sn, I, Cs, Eu, Hg, Pb, Bi, Ra, Th, Pa, U, Np, Pu, and Am in saline conditions. This was conducted by:

1. Experimentally measuring sorption coefficients for elements Cs(I), Pd(II), Sn(IV), Zr(IV), and Th(IV) onto Canadian sedimentary rocks (shale and limestone) and bentonite in a highly saline Na-Ca-Cl solution with TDS of 275 g/L (ionic strength of 6.0 m (mol/kgw)) by both batch sorption tests (up to 195 days) and long-term (1 year) through-diffusion tests; and
2. Performing a literature review to find any new sorption data for these elements relevant to Canadian sedimentary rocks and bentonite clay in saline conditions.

Sorption measurements were also conducted in Na-Ca-Cl dilute solutions with TDS of 0.5 g/L (ionic strength of 0.01 m) to investigate the effect of ionic strength on sorption. Two technical reports are expected in 2017, one documenting the sorption experimental measurements for elements Cs(I), Pd(II), Sn(IV), Zr(IV) and Th(IV), and another documenting the updated sorption database.

The Southwest Research Institute pioneered batch sorption measurements for six key redox-sensitive elements: Se(-II), As(III), Pu(III), U(IV), Tc(IV) and Np(IV). The experiments were conducted using Canadian sedimentary rocks (shale and limestone) and bentonite under controlled reducing conditions, as would be expected within a DGR (-150 mV ~ -200 mV), in synthetic porewater brine solutions (SR-270-PW, Na-Ca-Cl type, I = 6.0 M) and dilute solutions (Na-Ca-Cl type, I = 0.01 M) (Bertetti 2016).

A three-year research program was initiated in 2014, in collaboration with McMaster University, to study the sorption properties of Np onto bentonite, shale and illite, the latter of which is the primary mineral-sorbing radionuclide in shale in highly saline solutions, under both oxidizing (as Np(V)) and reducing (as NP(IV)) conditions. The sorption coefficients of Np onto bentonite, shale and illite in the synthetic porewater brine solution (SR-270-PW) were measured under oxidizing (Eh = 230 ~ 450 mV) and reducing (Eh = -130 ~ -220 mV) conditions. It was found that K_d values of Np(IV) were about three orders of magnitude larger than K_d values of Np(V). The effects of ionic strength and pH on the sorption of Np onto bentonite, shale and illite were systematically investigated in the highly saline solutions. Under oxidizing conditions, the K_d values for Np(V) on illite and shale were independent of ionic strength in the range of 0.1 – 4.8 M being investigated, the K_d values on bentonite decreased with increasing the ionic strength from 0.1 to 1.0 M but were independent of the ionic strength at greater than 1.0 M. Under reducing conditions, the K_d values for Np(IV) on illite, shale and bentonite slightly decreased with increasing ionic strength from 0.1 to 0.5 M but were independent of the ionic strength at greater than 0.5 M (Figure 4-6). A technical report documenting the sorption measurements for Np in highly saline solutions is expected in 2017. The measured sorption K_d values for Se, As, Pu, U, Tc and Np under reducing conditions are being used to update the NWMO's sorption database for Canadian sedimentary rocks and bentonite, to allow for use in the evaluation of potential DGR sites.

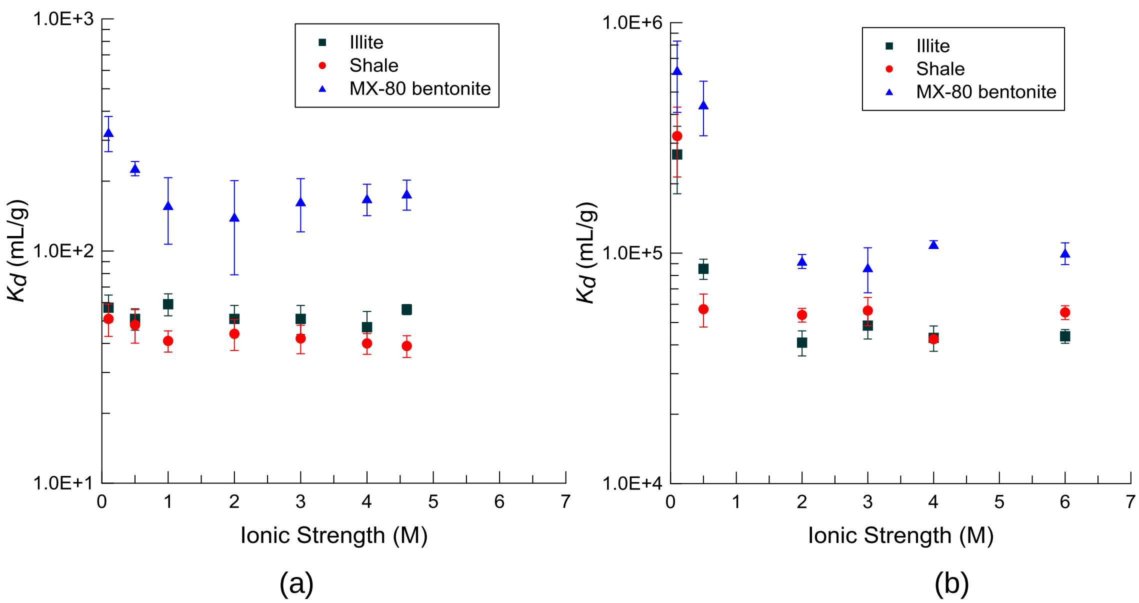


Figure 4-6: (a) Ionic Strength Dependence of Np(V) K_d Values in NaCl-$CaCl_2$ Solutions; and (b) Ionic Strength Dependence of Np(IV) K_d Values in NaCl-$CaCl_2$ Solutions (I = 0.1 – 4.2 m) and NaCl-$CaCl_2$-$NaClO_4$ Solutions (I = 6.0 m). The Initial Concentration of Np(V) Was 1.0×10^{-5} mol/L. The Initial Concentration of Np(IV) Was 1.0×10^{-11} mol/L

4.1.2.4 Reactive Transport Modelling

Reactive transport modelling is a useful approach for assessing long-term geochemical stability in geological formations. Reactive transport modelling is used to assess: 1) the degree to which dissolved oxygen may be attenuated in the recharge region of the proposed host rock; 2) how geochemical reactions (e.g., dissolution-precipitation, oxidation-reduction, and ion exchange reactions) may affect groundwater salinity (density) along flow paths; 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 in crystalline rocks 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-NWMO) 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. 2011a, 2011b, 2015). Previous code enhancements included: 1) calculation of ion activity corrections in high ionic strength solutions (up to 20 mol/L) using the Harvie-Möller-Weare model, which is based on the Pitzer equations; 2) calculation of fluid density for high ionic strength solutions; 3) one-dimensional hydromechanical coupling due to ice sheet loading; and 4) coupled heat, fluid and solute transport.

The most recent version of MIN3P-NWMO (MIN3P-THCm) has been further developed to simulate diffusion-controlled transport in low-permeability media (Xie et al. 2015a). The code enhancements include:

1. Implementation of the Nernst-Planck equation, which allows the simulation of electrochemical migration in multicomponent electrolyte solutions, in lieu of Fickian diffusion;
2. Extension of the multicomponent diffusion (MCD) code to radial coordinates;
3. Implementation of multisite ion exchange; and
4. Enhancement of the Nernst-Planck MCD code to include species-dependent accessible porosities and tortuosities to facilitate the simulation of anion exclusion and cation migration on mineral surfaces (hybrid MCD formulation).

MIN3P-THCm has been used to simulate the in-situ DR-A (Disturbances, Diffusion and Retention) diffusion experiments (with tracers HTO, I, Br, ^{85}Sr, Cs, ^{60}Co, and Eu) at the Mont Terri Underground Rock Laboratory (http://www.mont-terri.ch) and a series of associated benchmarking tasks (Xie et al. 2014). The simulation results have been compared with other reactive transport codes (including CrunchFlow, PHREEQC, and Flotran) and with in-situ experimental data. For the benchmarking tasks, excellent agreement was achieved with modelling groups using other reactive transport codes. The current model is capable of simulating conservative and reactive tracer diffusion in clayey materials such as the Opalinus Clay.

A parallel version of MIN3P-THCm (ParMIN3P-THCm) that can run on various platforms ranging from multicore desktop PCs, shared-memory workstations, to distributed-memory supercomputers has been developed (Su et al. 2015). The performance analysis has shown that a speedup greater than 100 is easily achievable with ParMIN3P-THCm.

The MIN3P-THCm development team has participated in an international benchmarking exercise entitled SSBench (Subsurface Environmental Simulation Benchmarks). The intent of this exercise was to develop and publish a set of well-described benchmark problems that can be used to demonstrate simulator conformance with norms established by the subsurface science and engineering community (Steefel et al. 2015a). The results of the benchmarking exercise have been published in a special issue of Computational Geosciences (see Steefel et al. 2015a, 2005b for an overview). MIN3P-THCm was used in seven of the benchmark problems (Alt-Epping et al. 2015; Marty et al. 2015; Mayer et al. 2015; Molins et al. 2015; Perko et al. 2015; Rasouli et al. 2015; Xie et al. 2015b). Several of the benchmarks are directly relevant to the long-term geological storage of nuclear waste, including the simulation of multispecies diffusion in bentonite (Alt Epping et al. 2015), reactive transport across a cement/clay interface (Marty et al. 2015), decalcification of cracked concrete (Perko et al. 2015), coupled multicomponent diffusion and electrochemical migration (Rasouli et al. 2015), and the evolution of porosity, permeability and tortuosity as a function of mineral-dissolution/precipitation reactions (Xie et al. 2015b).

In 2014, a three-year research program was initiated to further develop MIN3P-THCm to enhance model capabilities for simulation of reactive transport on both the regional and basin scale. The model enhancements include:

1. Unstructured computational grids to more effectively simulate reactive transport in complex geological geometries, such as inclined bedrock layers in sedimentary basins;
2. A new biogeochemical sulfate reduction model to account for the inhibition effect of hypersaline solutions on the bacterial dissimilatory reduction of sulfate; and
3. New features to aid in the assignment of rock-type dependent material properties, the corresponding flow and geochemical initial conditions, and transient 3-D boundary condition assignment of the ice sheet thickness contribution for the glaciation/deglaciation cycles.

The enhanced code was applied to investigate the formation mechanisms for sulfur water observed in the Michigan Basin. The salinity-dependent sulfate reduction model provides a possible explanation for the observations by Carter (2012) that sulfur water exists at intermediate depths, but not in the deep subsurface. Two technical reports are expected in 2017, one documenting the implementation of unstructured grids in MIN3P-THCm, and one documenting the reactive transport simulation of sulfur water formation mechanisms in the Michigan Basin.

Research work will be continued in 2017 to complete the implementation of unstructured grid capabilities in MIN3P-THCm for 3-dimensional systems, including the parallelization of the unstructured grid functions, and to perform benchmarking simulations contributing to the international SSBench code inter-comparison.

4.1.3 Seismicity

4.1.3.1 Northern Ontario Seismic Monitoring

The Canadian Hazards Information Service (CHIS), a part of the Geological Survey of Canada (GSC), continues to conduct a seismic monitoring program in the northern Ontario and eastern Manitoba portions of the Canadian Shield. CHIS maintains a network of sixteen seismograph stations to monitor low levels of background seismicity in these regions. This program has been on-going since 1982 and is currently supported by a number of organizations, including the NWMO. A key objective of the monitoring program is to observe and document earthquake activity within the Ontario portion of the Canadian Shield. All the stations are operated by CHIS and transmit digital data in real-time via satellite to a central acquisition hub in Ottawa. CHIS staff in Ottawa integrate the data from these stations with those of the Canadian National Seismograph Network and provide monthly reports of the seismic activity in northern Ontario.

The seismic activity in the study area during the calendar year 2015 consisted of 51 earthquakes ranging in magnitude from 1.2 m_N to 3.3 m_N (Figure 4-7). Seventeen earthquakes were larger than m_N 2.0. The largest event, with a magnitude of 3.3 m_N, occurred in the Témiscaming area, while the second largest event 3.1 m_N, occurred in Sudbury. The 51 events detected in 2015 compares with the average of 60 per year from the prior 4 years. An in-depth discussion of the seismic monitoring results from 2015 are provided in Adams et al. (2016).

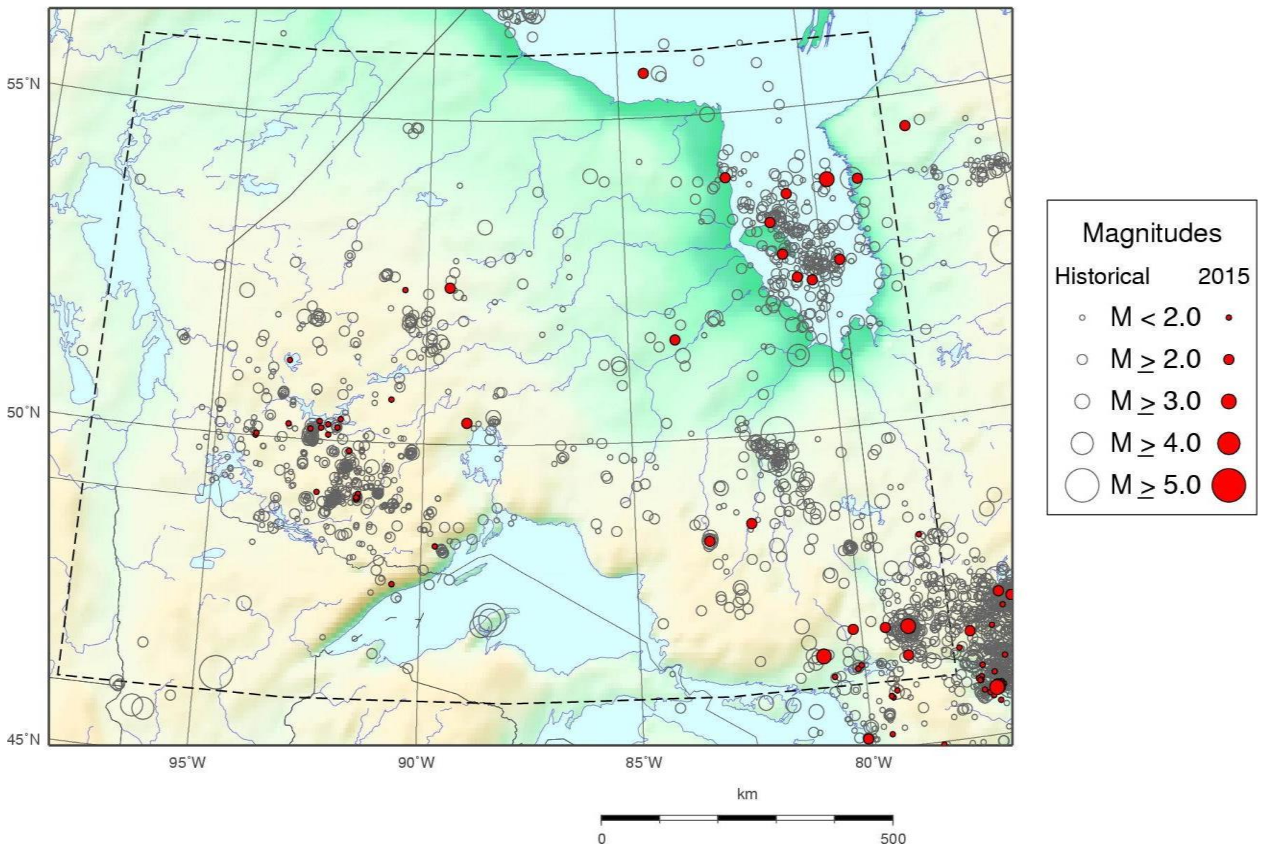


Figure 4-7: Earthquakes in Northern Ontario and Adjacent Areas from 1985 to 2015

4.1.3.2 Paleoseismicity

A key objective of the Applied Geoscience Research program is to advance the understanding of geosphere stability and its resilience to long-term perturbations. Brooks (2014) identified an integrated seismo- and chrono-stratigraphic methodology, as the best method to develop a long-term earthquake catalogue, from the investigation of disturbed deposits in lake basins. This work program, from 2014 to present, documents the paleoseismicity of the Rouyn-Noranda region on the Canadian Shield, Quebec, with the aim to advance understanding of post-glacial seismicity, which is relevant to APM DGR siting and site characterization activities, as well as safety case development.

Since 2013, in collaboration with the NWMO, the Geological Survey of Canada (GSC) has conducted an on-going program investigating the paleoseismicity of eastern Canada. The second phase of this project studied a watershed-scale region of northwestern Quebec and northeastern Ontario, which was selected due to its similarities in geology and post-glacial history with the Canadian Shield of northern Ontario. The associated fieldwork program identified the widespread occurrence of landslide deposits younger than 10,000 years before present (BP), buried within the glacio-lacustrine sediments of lakes within the study area. These landslide deposits, used to define potential event horizons, were identified from sub-bottom profiling returns. Through coring of these deposits, chronological data was obtained that allowed numerous multi-landslide horizons in adjacent lakes to be age-correlated. Several of these horizons have subsequently been interpreted as strong evidence for paleoseismic events.

Landslide horizons form a significant portion of the sub-bottom of the Lac Dasserat study area (Figure 4-8). The majority of the 74 mapped deposits fall within four event horizons. Horizons E and B exhibit strong multi-landslide signatures, while the signatures of horizons H and G are moderately strong. The single and paired deposits of horizons D, C, and A represent minor landslide signatures. Older unmapped and undated landslide deposits are present within the lower part of the sub-bottom. Coring programs were conducted in 2015, with results published as a series of open file reports, followed by the publication of a paper in January 2016 (Brooks 2016).

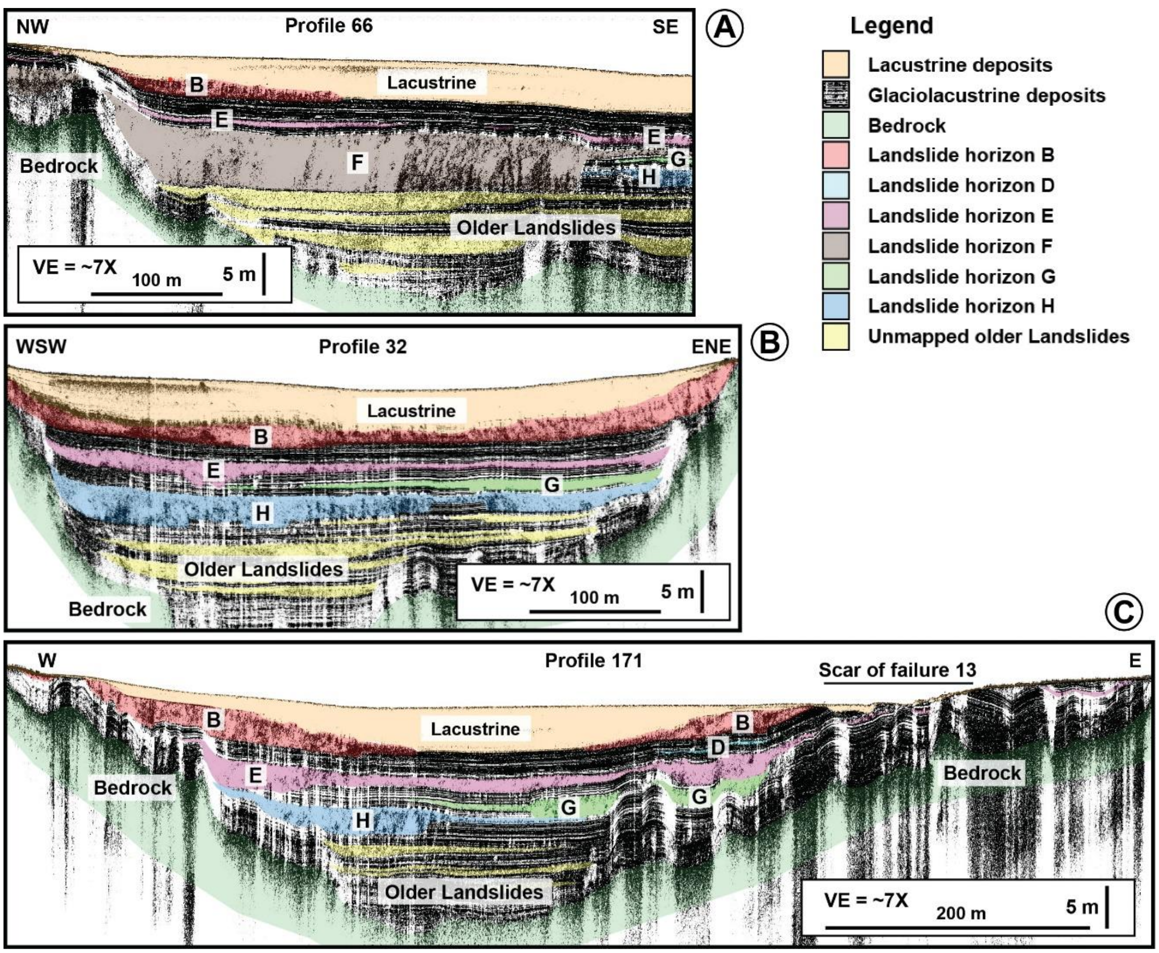


Figure 4-8: Three Examples of Interpreted (A, B, and C) Sub-bottom Acoustic Profiles; Although Event Horizons H, G, E, and B are Present in the Three Profiles, No Single Profile Within the Study Area Contains all Eight of the Mapped Event Horizons. Landslide Deposits Form a Significant Portion of the Sub-bottom and There are Older Unmapped Deposits (Shaded Yellow) in the Lower Portion of the Sub-bottom

The study revealed that across the study area (Figure 4-9) there are several strong landslide signatures that correspond to the same varve years (vyr) or varve ages. These interpreted paleoearthquakes occurred between vyr ~800 to 2100 (9770 ± 200 to 8470 ± 200 calibrated years BP) during regional deglaciation when glacial Lake Ojibway was impounded behind the Laurentide Ice Sheet. They may represent a period of elevated seismicity associated with crustal unloading, arising from the retreat of the ice sheet, that occurred within an area now experiencing low historical seismicity.

This study demonstrates the application of an integrated seismo- and chrono-stratigraphic approach to investigate evidence of paleoseismicity preserved in late glacial deposits within a lake basin of eastern Canada. The landslide deposits used to define the event horizons could all be mapped exclusively from the profiling returns, which would have identified the multi-landslide signatures. However, it was only through recovering core that the crucial chronological data was obtained that allowed three of the four multi-landslide horizons to be correlated to disturbed varve deposits mentioned in the regional literature, thereby helping corroborate the paleoearthquake interpretations. The identification of four paleoearthquakes, and the possible period of elevated seismicity during deglaciation, provide an interpretative framework that can be augmented and revised by future paleoseismic research in northwestern Quebec-northeastern Ontario. The results of this phase of the project will be documented in a technical report to be published in 2017.

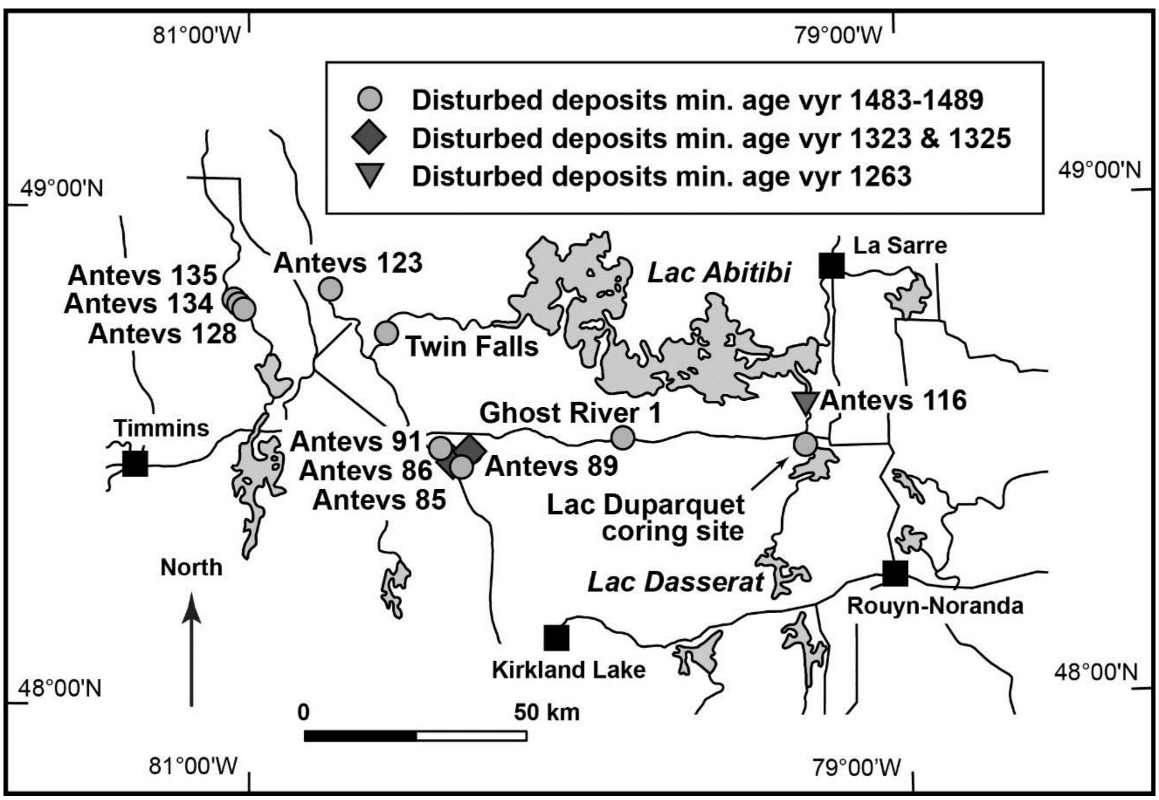


Figure 4-9: Map Showing Locations of Varve Sampling Sites of Antevs (1925, 1928), Hughes (1959), and Breckenridge et al. (2012) Where the Varve Ages of Disturbed Deposits are Essentially Identical to Lac Dasserat Event Horizons H, G, or E. The Ages (or Age Ranges) Shown in the Legend are Derived From the Varve Number (Less One Year) of the Youngest Undisturbed Varve Overlying a Disturbed Deposit

4.1.4 GEOMECHANICS

The various work programs in the area of geomechanics focus on ensuring the NWMO's ability to characterize: 1) the integrity of the rock mass, 2) the extent of damage to said integrity associated with drilling and excavation activities, and 3) the long-term response of the rock mass to natural and induced stresses.

4.1.4.1 POST

In a crystalline rock setting, it is a highly likely that the access tunnels and emplacement rooms of a Deep Geologic Repository (DGR) will encounter fractures within the rock mass. The fractures may occur at multiple scales, from those within the Excavation Damage Zone (EDZ) to regional scale faults. Regardless of scale, one must incorporate these features into the repository design and post-closure analysis and assess their implication to long-term safety. In this regard, guidelines are required for Rock Mass Characterization (RMC) to ensure safe implementation of the DGR concept; otherwise, from a practical perspective, large volumes of potential repository space may be lost due to inappropriate exclusion.

Fracture Parameterisation for repository design and post-closure analysis (POST) was initiated in the Spring of 2014 in collaboration with Posiva Oy, SKB (Svensk Kärnbränslehantering AB) and the NWMO (Nuclear Waste Management Organisation). The objective of this collaborative work was to develop a strategy and guidelines for determining the necessary parameters to assess fracture stability (shear displacement) at the deposition-tunnel scale for repository design, and, in the context of safety assessment, canister integrity. The program consisted of field characterization of rock joints, laboratory and *in situ* shear tests, as well as numerical simulations. A key issue to address was the estimation of fracture shear displacement in the underground environment as a function of laboratory testing conducted under constant normal load (CNL) and constant normal stiffness (CNS). The project terminated because proper testing frames for the POST requirements (i.e., for the large scale laboratory shear testing) were unavailable. A description of POST and its development is documented in Siren et al. (2016).

The current phase of POST (POST 2016) is organized as a collaboration between SKB and the NWMO and has similar, but refined, objectives. These objectives are to:

1. Investigate the shear behaviour of large natural fracture samples under CNS boundary conditions and subjected to a 50 mm shear displacement.
2. Study scale effect in the behaviour of natural fracture(s) under CNS conditions with large displacement.
3. Investigate if fracture replicas can reproduce the behaviour of natural fractures repeatedly under CNL and CNS conditions.
4. Study the scale effect in artificially tensile induced fracture under CNL and CNS conditions.

The project will involve the development of a large scale laboratory shear box in Sweden in which quarried fracture samples and replicates at various scales will be sheared to 50 mm under various CNS conditions to illustrate up-scaling properties and the conservatism in historical CNL parameter estimates. A large four-pillar loading frame exists at the Research Institute of Sweden (RISE) laboratory in Borås, Sweden (Figure 4-10). This loading frame has adequate capacity to deliver the required high normal stress on the specially-built shear box for large scale fracture testing. This laboratory shear test was intended to substitute the more expensive in-situ tests on large scale fractures proposed in the last phase of POST. It was estimated that the maximum capacity of the test frame would enable the shearing of a fracture sample measuring up to 300 mm by 500 mm^2 under a constant normal load of up to 20 MPa. This normal stress would correspond to the ground stress encountered in a repository at a depth of approximate 430 m. Results of the laboratory shear testing will be subject to numerical analysis by independent SKB and NWMO geomechanical modelling teams to evaluate and verify constitutive relations used to simulate and estimated shear behaviour. This information is essential to building confidence in estimates of shear displacement that underpin the development of practical guidelines necessary to assess the suitability and acceptability of site-specific depositional hole and/or emplacement room conditions. The POST 2016 project is scheduled to be completed in 2019.

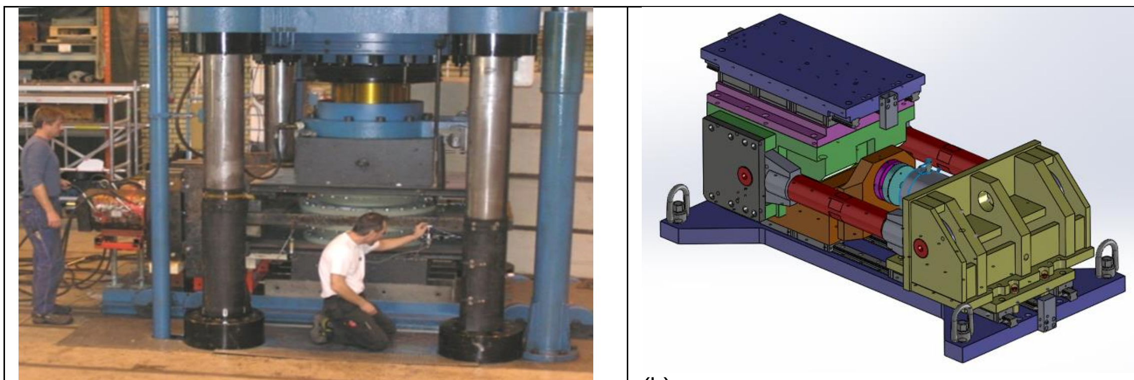

(a) (b)

Figure 4-10: Large Capacity Four-column Load Frame With Maximum Normal Capacity of 20 MPa and Maximum Height of 4 m, Research Institute of Sweden; (b) Conceptual Design of Large-scale Shear Box

4.1.4.2 Synthetic Rock Mass

The multi-year Synthetic Rock Mass (SRM) research program came to an end in 2016. This program was co-funded by Svensk Kärnbränslehantering AB (SKB) and the NWMO. The program brought together researchers from the University of Alberta and Queen's University, with focus on the advancement of numerical modelling approaches for the prediction of rock mass response to applied loading, in order to facilitate the design and excavation of an underground repository in crystalline or sedimentary rock. The ability to forecast rock mass response using model prediction far exceeds the traditional design expectations for underground civil or mining projects. The objective of this research was to:

1. Advance current understanding of rock mass strength;
2. Develop methodologies for assessing the strength and incorporating scale effects;
3. Develop methodologies for assessing rock mass behaviour subjected to coupled processes; and
4. Develop numerical tools that can be used during the design, construction and performance evaluation of an underground nuclear waste repository.

The study was divided into: (1) grain-based (micro) modelling (GBM), (2) sample/block (meso) scale modelling of intact rock, and (3) larger/excavation (macro) scale modelling incorporating the joint and bedding system. Figure 4-11 demonstrates the use of the grain-based modelling approach to construct a Lac du Bonnet (LdB) granite sample. To create heterogeneity, as in the natural LdB granite, four grains types were introduced and were distributed into the SRM model according to the abundance of each mineral. Figure 4-11 also shows an example of mineral distribution – comparing between natural granite and models generated by the SRM approach (Farahmand 2017). For sample- and excavation-scale modelling, the complex behaviour of the grain strength and sub-block boundaries has been investigated to better understand the role of boundary fracturing (Day 2016). Mechanical testing on scaled rock samples and numerical validation was also performed (Farahmand 2017).

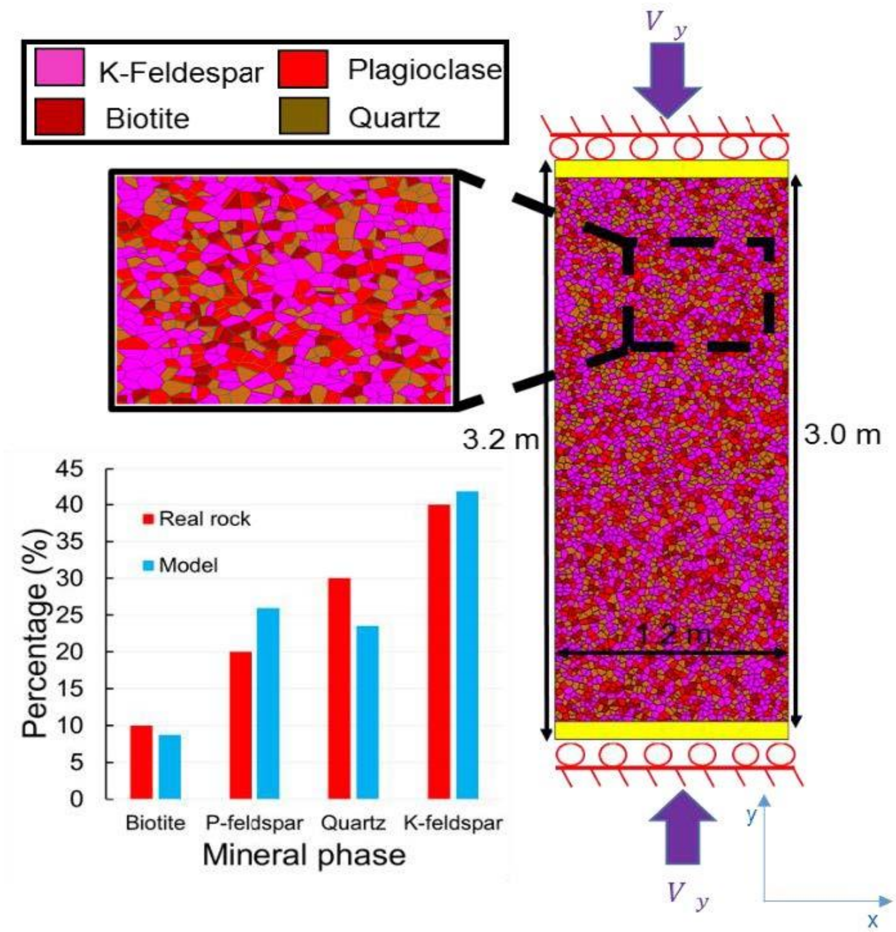


Figure 4-11: SRM Model for an Unconfined Compression (UCS) Test Sample. Grains with Purple, Light Red, Light Brown, and Dark Red Represent K-feldspar, Plagioclase, Feldspar, Quartz and Biotite Minerals, Respectively; Histogram Shows the Abundance of Different Mineral Phases (Farahmand 2017)

Traditional approaches, using rock mass classification systems derived from practical observations, are very effective for engineering design but are not as well suited for safety and performance assessment, in which up-scaling can play an important role. To better account for the issue of scaling, the SRM approach could be utilized through discrete fracture modelling. In the SRM research at Queens University, the scale-dependency of mechanical properties were examined using a series of UCS test simulations, with sample diameters ranging from 1 to 10 m. As anticipated, both stiffness and strength of the SRM samples reveal a decreasing trend as the sample size increases (Figure 4-12 and Figure 4-13). This demonstrates the capability of the grain-based SRM models to reproduce the mechanical behaviour of rock in the laboratory sample scale.

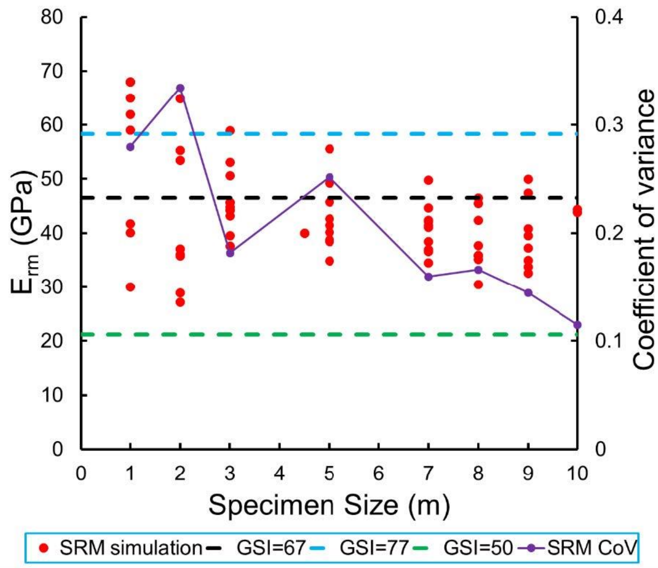


Figure 4-12: Elastic Modulus Obtained from SRM Simulations and Empirical Hoek-Diederichs Equation (Hoek and Diederichs 2006) for Different Specimen Sizes (Farahmand 2017)

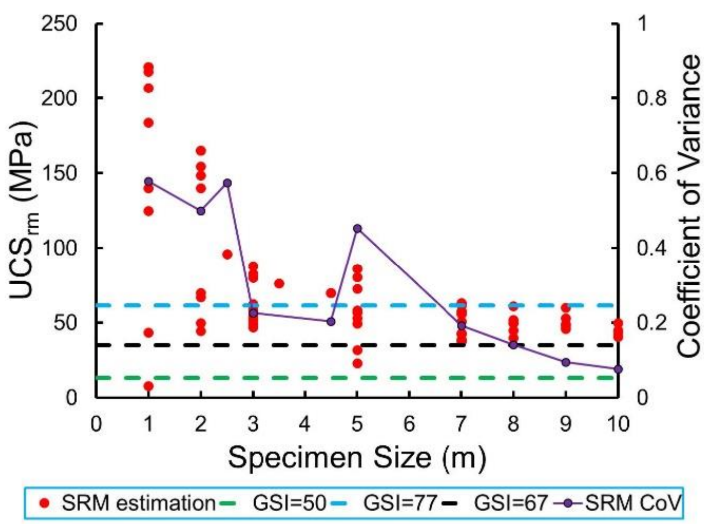


Figure 4-13: Compressive Strength Obtained from SRM Simulations and Hoek-Brown Criterion for Different Specimen Sizes [Note: Input GSI parameter in the Hoek-Brown criterion was estimated based on the average block volume, mean joint spacing and RQD measured in the Brockville site (Farahmand 2017)]

Approaching the challenge of synthetic rock mass modelling from another direction, work was carried out to examine and redefine procedures for collecting data (field and testing lab) for input into field-scale discontinuum models. This work (Day 2016) explored scale and confinement effects on joint shear and normal stiffness – two parameters that have not been explored as deeply as shear strength parameters. The accuracy of joint stiffness parameters used in SRM or discontinuum models does, however, have significant impact on the outcome, in terms of both displacement and the overall nature and scale of damaged zone prediction. Accurate direct shear testing procedures can also highlight otherwise overlooked differences between rock units. In Figure 4-14, shear stiffness of Cobourg/Lindsay Limestone from approximately 700 m depth at the Bruce nuclear site is compared with samples obtained from near surface at the St. Mary's Quarry, in Bowmanville, Ontario.

The SRM modelling takes a novel approach to simulate the fracture of intact rock and the deformation along existing discrete fractures, in comparison to the traditional continuum and discontinuum methods, using Discrete Element logic to capture the failure of the individual components and their interactions. A final summary report capturing the five-year research will be published in 2018.

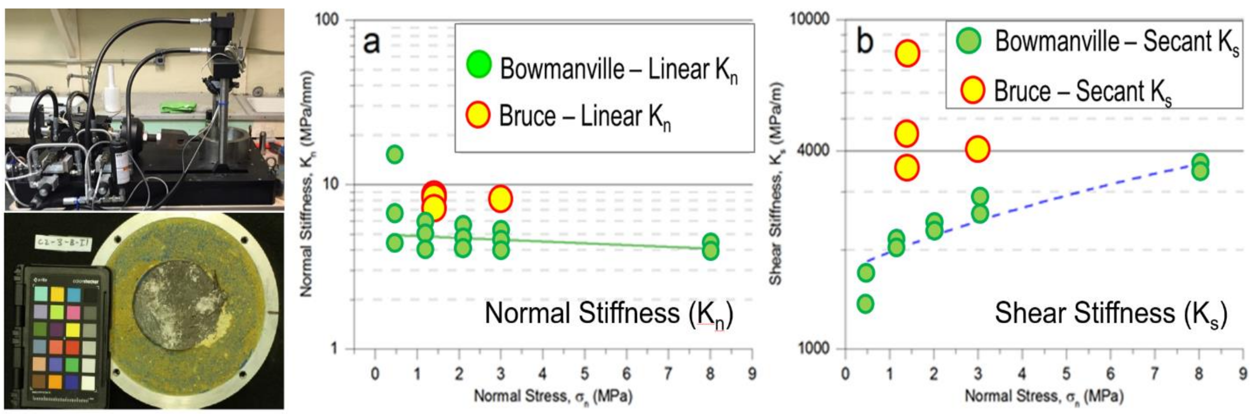


Figure 4-14: Servo Controlled Direct Shear Apparatus at Queen's University; (a) Normal and (b) Shear Stiffness Measurements from Two Different Limestones

A similar research program, to explore an alternative approach to investigate the ability to predict rock mass response using a Discrete Fracture Network (DFN) approach, was initiated in 2016. This three-year collaborative research project, sponsored by the NWMO, Posiva Oy (Posiva) and SKB, is being carried out by Itasca Consultant, S.A.S., in France. This is part of a larger DFN project related to on-going research between Posiva and SKB.

The aim of the work is to develop (and apply) a methodology to study how rock mass effective properties can be related to intact rock and DFN models through quantitative and analytical relationships. The recent development in SRM modelling, where discrete fractures are explicitly represented in rock models, opens promising pathways to predict the evolution of rock mass effective properties with scale, from a multi-scale DFN approach. The primary objective of the proposed work program is to improve conventional techniques through the simulation of rock mass response, based on the multi-scale nature of the DFN. The methodology developed will advance current understanding of the constitutive relationships between fractured system models (DFN and fracture mechanical model) and the rock mass mechanical parameters, such as elastic properties and failure envelope parameters of rock. The study aims to validate this methodology for rock mass models in various geological settings by including an effective and explicit representation of fractures into the modelling applications. The approach involves the application of discrete element logic in established numerical codes, such as DFM3D, UDEC and/or PFC3D, and the research is in progress. Results from the first year of the study has undergone peer review and publication is anticipated in the coming year (Day et al. 2017, *submitted and currently in press*).

4.1.4.3 Time-dependent Rock Strength

A time-dependent rock behaviour testing program was initiated in 2014 to investigate the static fatigue (constant axial load) and relaxation (constant axial strain) behaviour of the Jura and Cobourg limestones. The testing program at ETH Zurich aims to verify the argument that the lower bound strength for these limestones can be represented by their crack initiation (CI) thresholds. Empirical evidence from underground excavations (Martin 1997), numerical back-analysis (Diederichs 2007) and laboratory testing (Schmidtke and Lajtai 1986) suggests that the lower bound rock strength limit or long-term strength of rock could be approximated by a strength value equal to the CI threshold. This phenomenon was observed during laboratory static fatigue testing of Lac du Bonnet (LdB) granite from Pinawa, Manitoba, for which a finite strength threshold was observed at a driving stress ratio of about 0.45. This value coincides with the CI of the rock at about 45% of Unconfined Compressive Strength (UCS).

At ETH Zurich, static load creep (fatigue) and constant strain relaxation testing was undertaken on cylindrical and prismatic samples of the Cobourg limestone and the Jurassic (Jura) limestone from Switzerland (Figure 4-15). Currently, only the cylindrical samples are complete and a portion of the prismatic samples have been analyzed. It is anticipated that all testing will be completed in 2017. To date, despite the fact that limited tests have been completed, the times to failure observed indicate a similar trend to the LdB granite test results (Figure 4-16). However, the trend is shallower, meaning that at the same bound driving stress–ratio, the time required to failure of the limestone would be longer than that predicted for the LdB granite.

Both the Cobourg and Jurassic limestone samples showed that when tested at loads above the crack damage threshold (from UCS baseline test results) of approximate 80% of UCS, sample failures occur within an hour or less. On the other hand, for samples loaded at or below CI (40% of UCS), no failure was observed. When the applied loads range between CD and CI, failure may occur during the first hour, but may take up to one month (only observed in Jurassic limestone; Figure 4-15). The data suggests that there is no obvious trend, i.e., a decrease in strength with time, for samples that did not fail after one month (strength corresponding to about 70% of UCS).

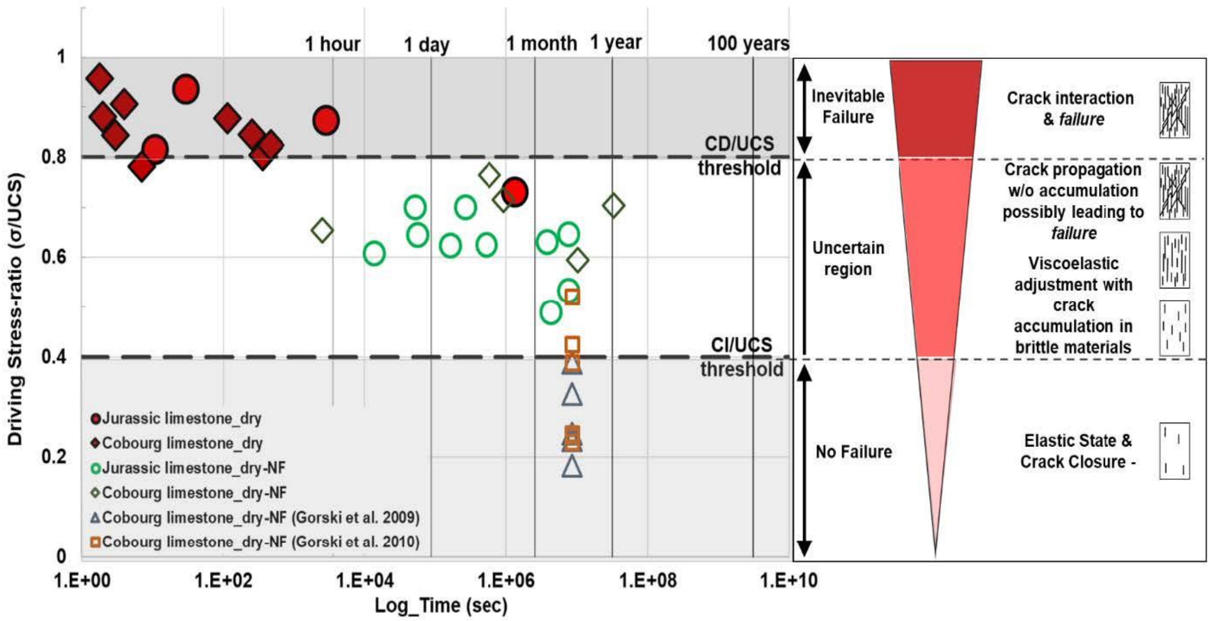


Figure 4-15: Static Load Creep Test of Jurassic and Cobourg Limestone Performed in Dry Conditions (The 'NF' in the legend indicates samples or tests did not fail)

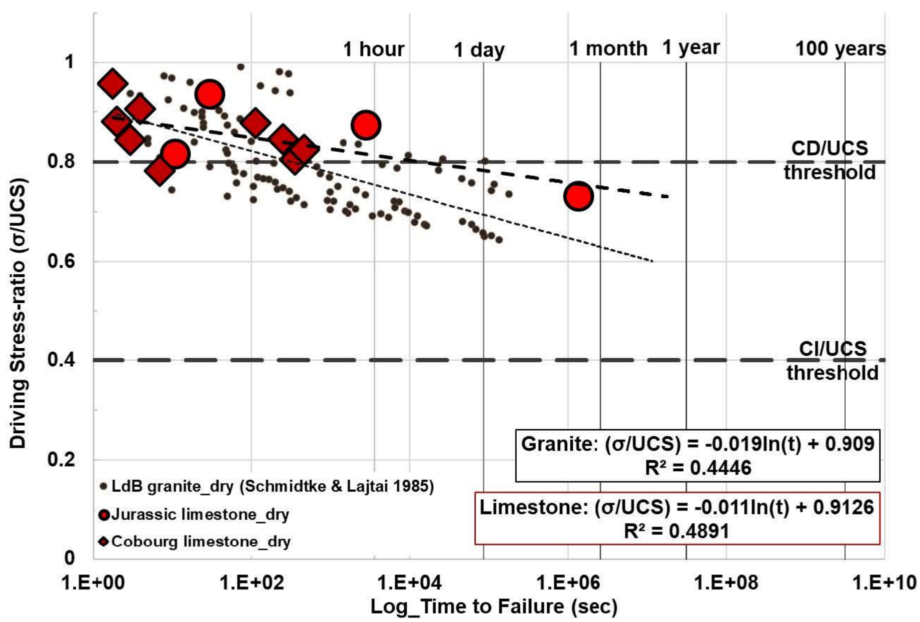


Figure 4-16: Comparison of Static Load Creep Test Data on Limestone and Granite Performed at Room Temperature in Dry Conditions

4.1.4.4 Fracture Network Software for Site Characterization

Fracture network modelling involves using 3-dimensional, geostatistical tools for creating realistic, structurally possible models of fracture zone networks within a geosphere that are based on field data. The ability to represent and manage the uncertainty in the geometry of fracture networks in numerical flow and transport models is a necessary element in the development of credible geosphere models. This approach directly honours and incorporates information available during preliminary site characterization, including:

- Detailed information on the locations of surface lineaments, which is typically available from aerial photography, remote sensing and/or ground reconnaissance;
- Regional tectonic information on stress, which can often help to constrain the style of fracturing: dominantly low-angle features in compressional regimes, dominantly sub-vertical in tensional regimes;
- Geomechanical and structural geology principles, which may assist with predicting down-dip behaviour of fractures; and,
- Field data gathered from geologically analogous sites, which may provide supporting information on fracture density, orientation and truncations.

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, has been 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. MoFrac is capable of creating discrete fracture network models at the tunnel-, site- and regional scale. The modelling of deterministic features allows MoFrac DFNs to be directly linked geospatially to field observations.

In addition to the on-going development of MoFrac, tunnel-scale model development was undertaken using detailed fracture mapping data from SKB's Äspö Tunnel Extension project. For the validation study, a section of the tunnel was selected in order to generate a discrete fracture network model. A broad suite of model features were validated as a part of this study, including fracture shape and undulation, orientation, intensity, and truncation rules. The model output was compared against the observed features from the Äspö tunnel extension project using optimal input parameters to characterize the fracture network. A second suite of scenarios, intentionally using extreme input parameters, were undertaken to highlight the effect on the generated discrete fracture network models. A comparison between mapped and model generated fracture traces is shown in Figure 4-17.

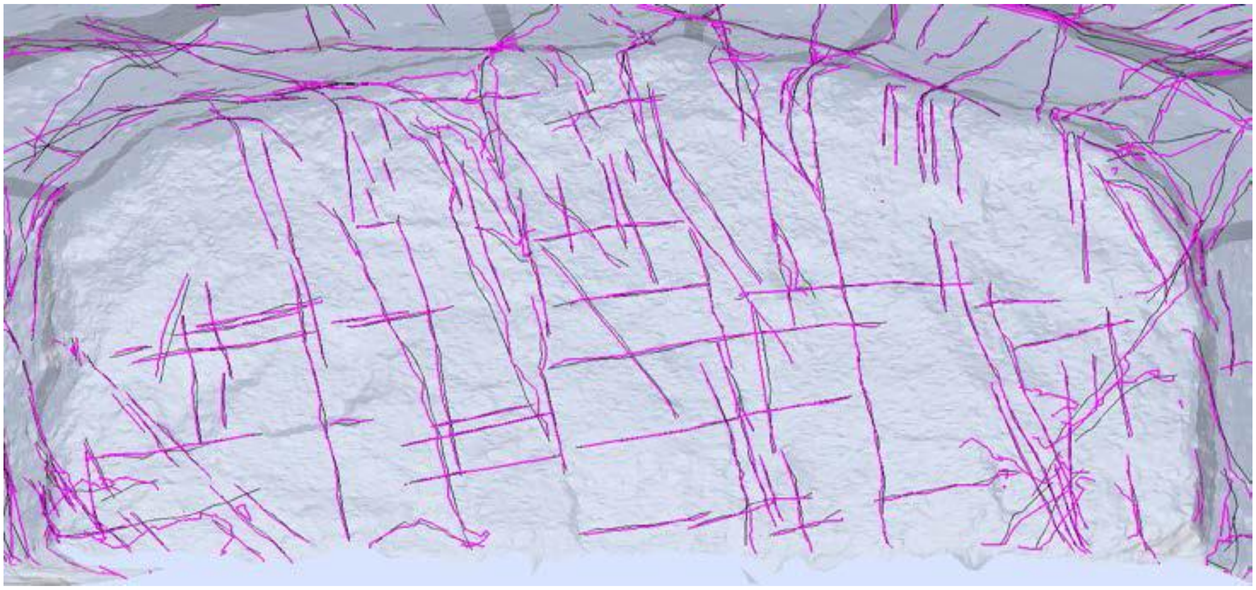


Figure 4-17: Comparison of Field (grey) and Generated Fracture (pink) Traces for Tunnel Wall

4.1.4.5 Effects of Saturation, Scale and Loading on Rock Properties

As part of an Excavation Damage Zone (EDZ) Study, the effects of saturation, scale, and loading rate on the geomechanical properties of the Cobourg limestone were investigated through the testing of 54 Uniaxial Compressive Strength (UCS) and 47 Brazilian Tensile Strength (BTS) specimens.

To investigate the effect of saturation on the stress-strain behaviour of the rock, six different drying and saturation methods were used. The testing reveals the longest saturation duration (based on water content measurements), three month submersion, did not produce significantly higher degrees of saturation for test samples when comparison to other methods. However, the three month saturation of samples could result in extensive chemical interaction between the rock and the Synthetic Pore Water (SPW) used to saturate the samples, which could result in some sample deterioration. The lack of increased water content, and the potential for specimen damage from this saturation method, suggests that shorter durations would be adequate for saturating test samples.

Increasing water content in UCS specimens has resulted in increased Poisson's ratio and decreased Young's modulus. The thresholds of CD, UCS, and BTS have shown a significant decreasing trend with increasing water content. CI threshold exhibits a more modest decrease with increasing water content, producing a small range in values that appears to approach a constant value at higher water contents (Figure 4-18). Saturation of the clay-rich layers of the rock in unconfined conditions is believed to be an important factor influencing the results of this study. The trends observed in this data are likely associated with the localized uptake of SPW into clay-rich lenses present in the Cobourg limestone.

The influence of specimen scale was studied using 12 UCS and 17 BTS specimens prepared with four different diameters ranging between 50 and 126 mm. The changing scale appeared to have no significant effect on the Poisson's ratio, CI, CD, or UCS of Cobourg limestone (Figure

4-19). Examination of the Young's modulus results have shown a consistent increase with specimen diameter.

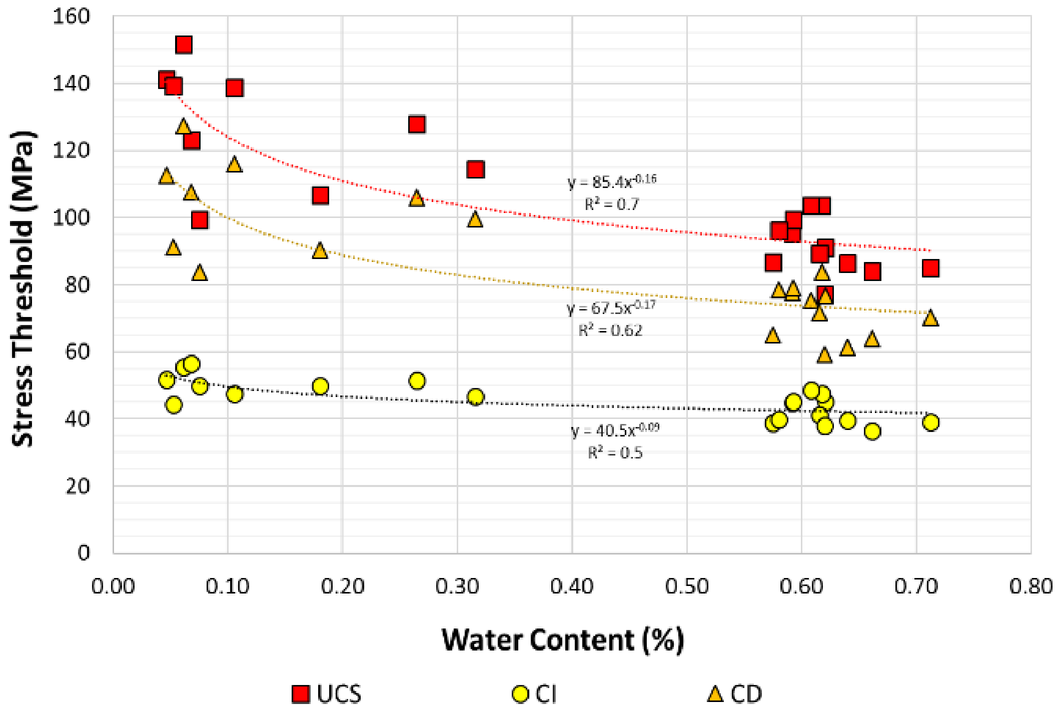


Figure 4-18: Comparison of CI, CD, and UCS Stress Thresholds with Respect to Specimen Water Content

The results of 24 UCS specimens were used to investigate the effect of loading rate on Room Relative Humidity (RRH) and one month saturated specimens using four different axial strain rates. The RRH specimen results show a decrease in CD and UCS threshold with increasing axial strain rate. On the other hand, Young's modulus, Poisson's ratio, and CI threshold remain relatively constant throughout all tested strain rates, suggesting no loading rate effects (Figure 4-20). The one month saturated specimens show the opposite trend of the RRH specimens for CD and UCS. These thresholds increase with increasing axial strain rate, while CI remains constant. There also appears to be a minor increasing trend in both Young's modulus and Poisson's ratio with increasing axial strain rate (Figure 4-21). It is likely that these properties remain relatively constant throughout the different strain rates.

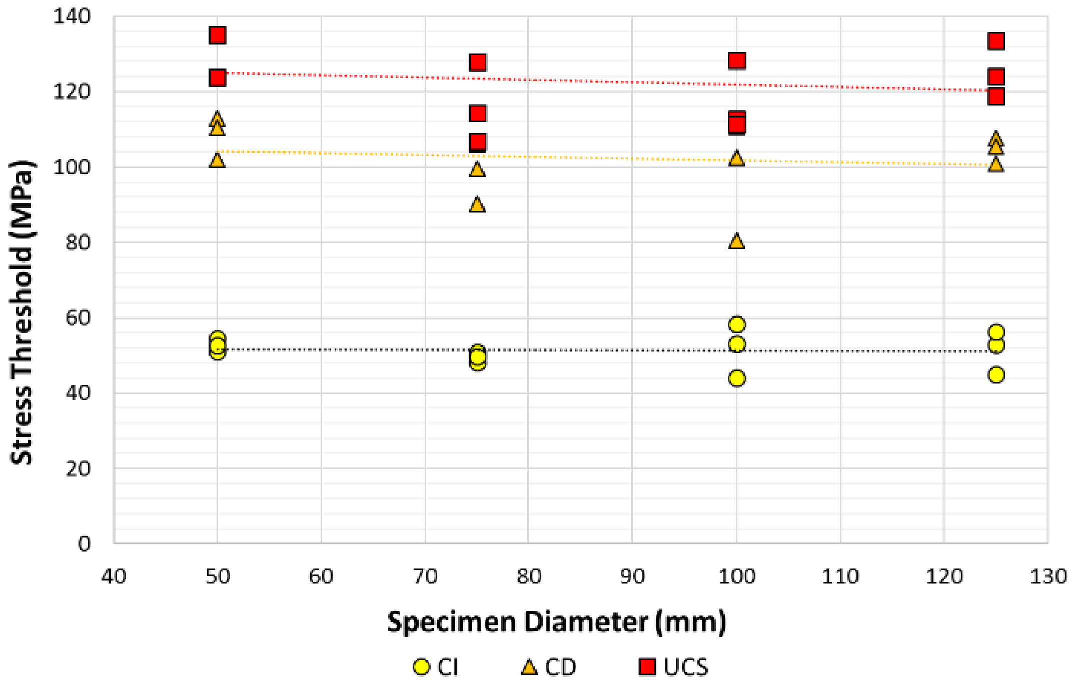


Figure 4-19: Comparison of CI, CD, and UCS Stress Thresholds with Respect to Specimen Diameter

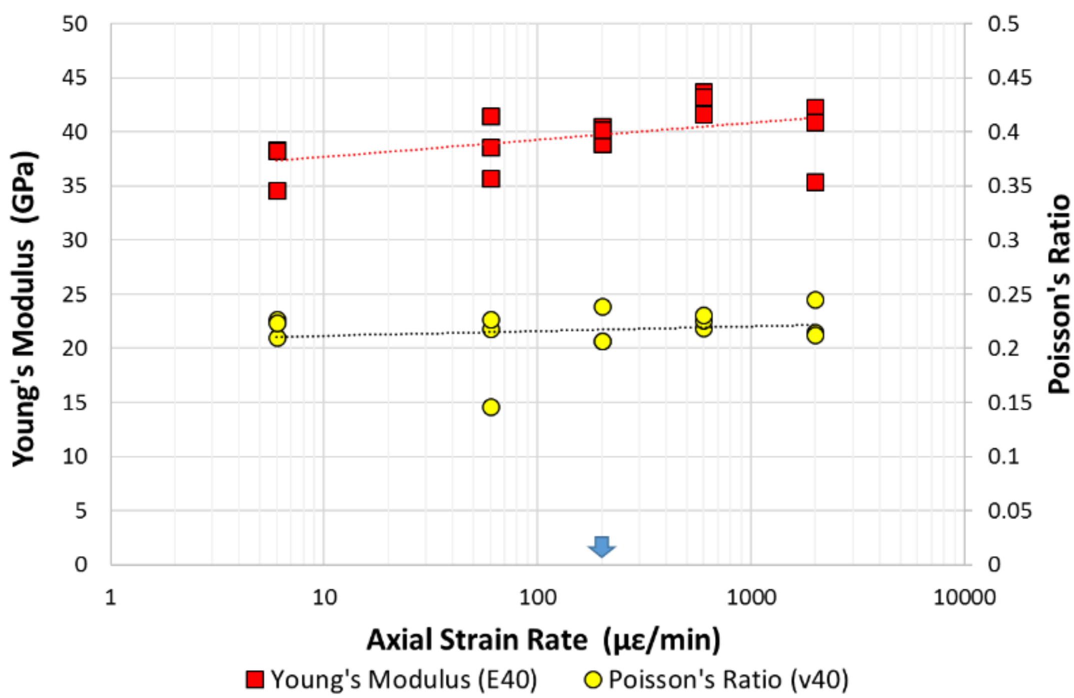


Figure 4-20: Poisson's Ratio and Young's Modulus Versus Axial Strain Rate for RRH. Blue Arrow Represents Standard Axial Strain Rate Used in Saturation and Scaling Studies

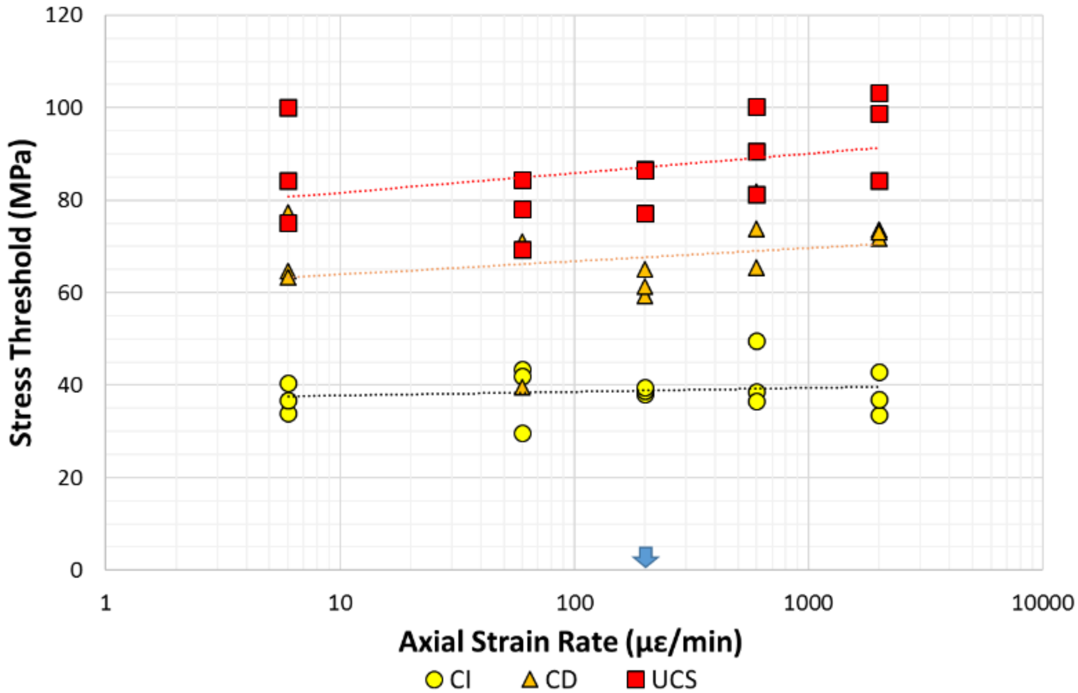


Figure 4-21: Comparison of CI, CD, and UCS Stress Thresholds with Respect to Axial Strain Rate for One Month Saturated Specimens. Blue Arrow Represents Standard Axial Strain Rate Used in Saturation and Scaling Studies

4.1.4.6 Mont Terri FE Project, Switzerland

In 2014, the NWMO was a project partner in several experiments at the Mont Terri Rock Laboratory, Switzerland. One of these experiments was the Full-scale Emplacement (FE) experiment, which commenced in 2013. This 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 and to investigate the thermo-hydro-mechanical (THM) coupled effects on host rock and the engineered barrier system (EBS) at a 1:1 scale (Vogt 2013). The general arrangement of the experiment is shown in Figure 4-22.

The installation of the heating elements and backfilling was completed as of 2015. A concrete bulkhead was also cast near the portal of the tunnel. The experiment is designed to simulate the heat generated by radioactive decay of used fuel containers under post-closure conditions. The behaviours of backfill material and rock under the influence of temperature are monitored by several hundred sensors to record temperature, pore-water pressure, water content and suction, as well as deformations and stresses within the bentonite backfill and host rock throughout the entire experiment duration. The monitoring program has completed its second year and measurements will continue over the next decade. Coupled THM modelling is currently being performed on CODE_BRIGHT (Olivella et al. 1996) using the instrumentation data collected (Garitte 2016). The back-analysis of the system response reveals a good qualitative agreement with observations from monitoring. Calibrations of THM parameters of bentonite backfill and host rock are currently in progress in order to gain understanding of the underlying processes. Figure 4-23 shows a two-dimensional model geometry of the experiment.

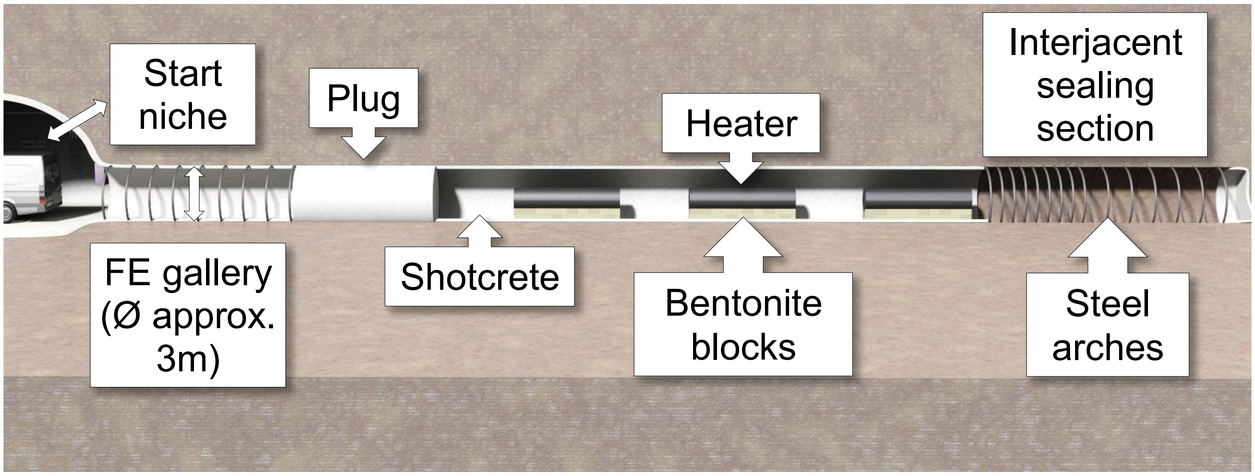


Figure 4-22: Visualization of Final Arrangement of FE Experiment at Mont Terri Rock Laboratory (Vogt, 2013)

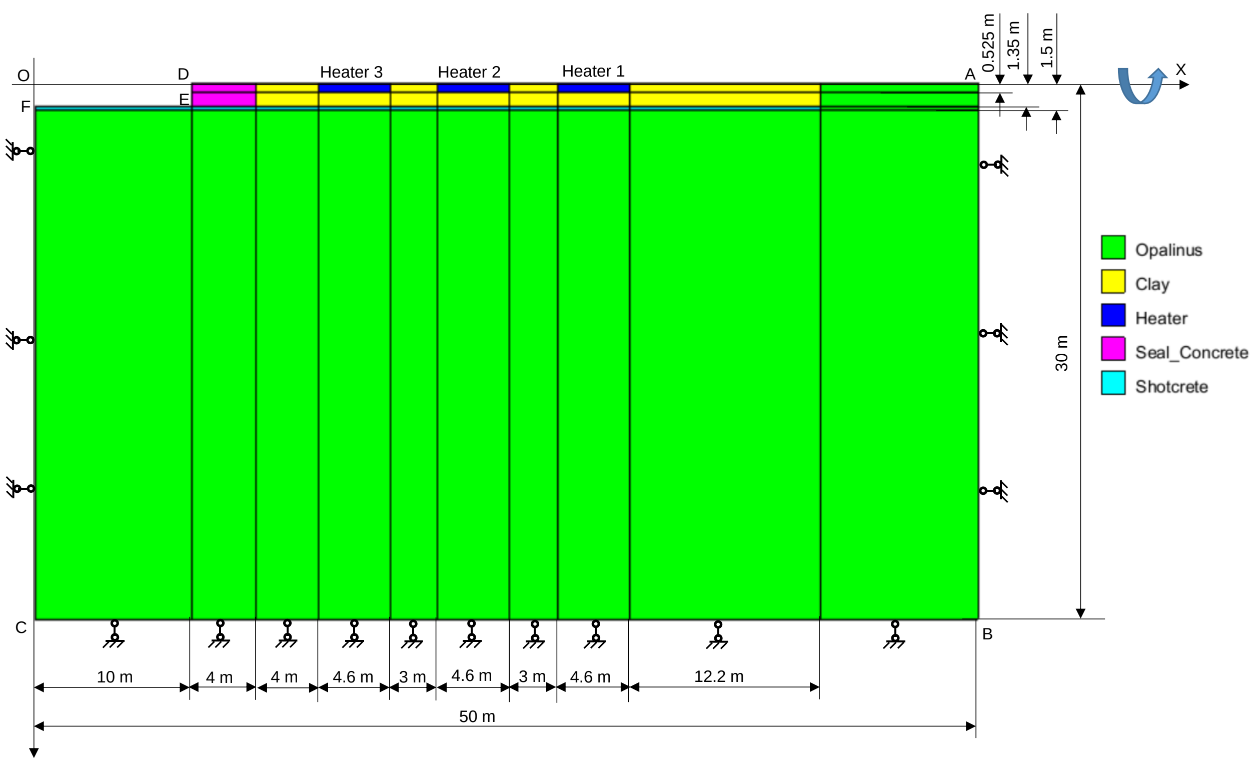


Figure 4-23: Two-Dimensional Axial-Symmetric Model of FE Experiment

4.2 GEOSPHERE EVOLUTION – CASE STUDIES

4.2.1 Geochemical Evolution and Paleohydrogeology

4.2.1.1 Geochronology and Fluid Inclusions

A key issue in the long-term safety assessment of a DGR is the need to demonstrate an understanding of the geological evolution of the potential host rock mass. Mineral-filled fractures and openings (e.g., veins and vugs) in a rock mass provide evidence that fluid migration events have occurred at some point in the geologic past. Vein and vug emplacement may be related to diagenesis (in sedimentary rocks), orogenic activity and/or uplift and erosion. Characterization of the infilling mineral phases, including absolute age determinations of the infilling material, can provide useful information regarding the tectonic history of the rock mass. Such information benefits the APM siting program as part of site characterization activities, where knowledge of geologic stability and fluid migration events are of importance.

As part of the broader study of fracture characterization, a program involving radiometric Uranium-Lead (U-Pb) age analysis of vein calcite is on-going at the University of Toronto's Jack Slattery Geochronology Laboratory. The work program has been progressively developed since 2013 and has demonstrated a robust 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. While this work program has so far focused on vein calcite in sedimentary rocks, it is envisaged that the methods and interpretative strategy developed will be suited to both sedimentary and crystalline rock environments, and will therefore develop readiness for site characterization activities.

A step-wise approach has been developed whereby an initial assessment of the radiogenic character (U and Pb isotope concentrations) of each calcite vein sample is made using LA-ICPMS. The rationale for this step is that only the most radiogenic samples would be suitable for precise age determination by ID-TIMS. For all samples, calcite vein material is first mechanically separated from the host rock and mounted on glass slides in preparation for spot ablation. Data on ^{206}Pb, ^{207}Pb and ^{238}U is then collected to provide age information. The results demonstrate that the methodology developed and employed during this project are feasible for understanding the timing of vein emplacement in Paleozoic sedimentary rocks.

A Technical Report that highlights the results from a recent two-year project (2014-2016) has been completed (Davis 2016; NWMO-TR-2016-07). This report summarizes all geochronology results for the Paleozoic section at the Bruce nuclear site (Figure 4-24), including previously reported results (Davis 2013). These previously reported ages have been updated since the 2013 report, based on alternative data processing techniques determined through analyses of the sensitivity of the LA-ICPMS method to different standards and laser wavelengths. The discussion of this method refinement is included in the 2014-2016 report.

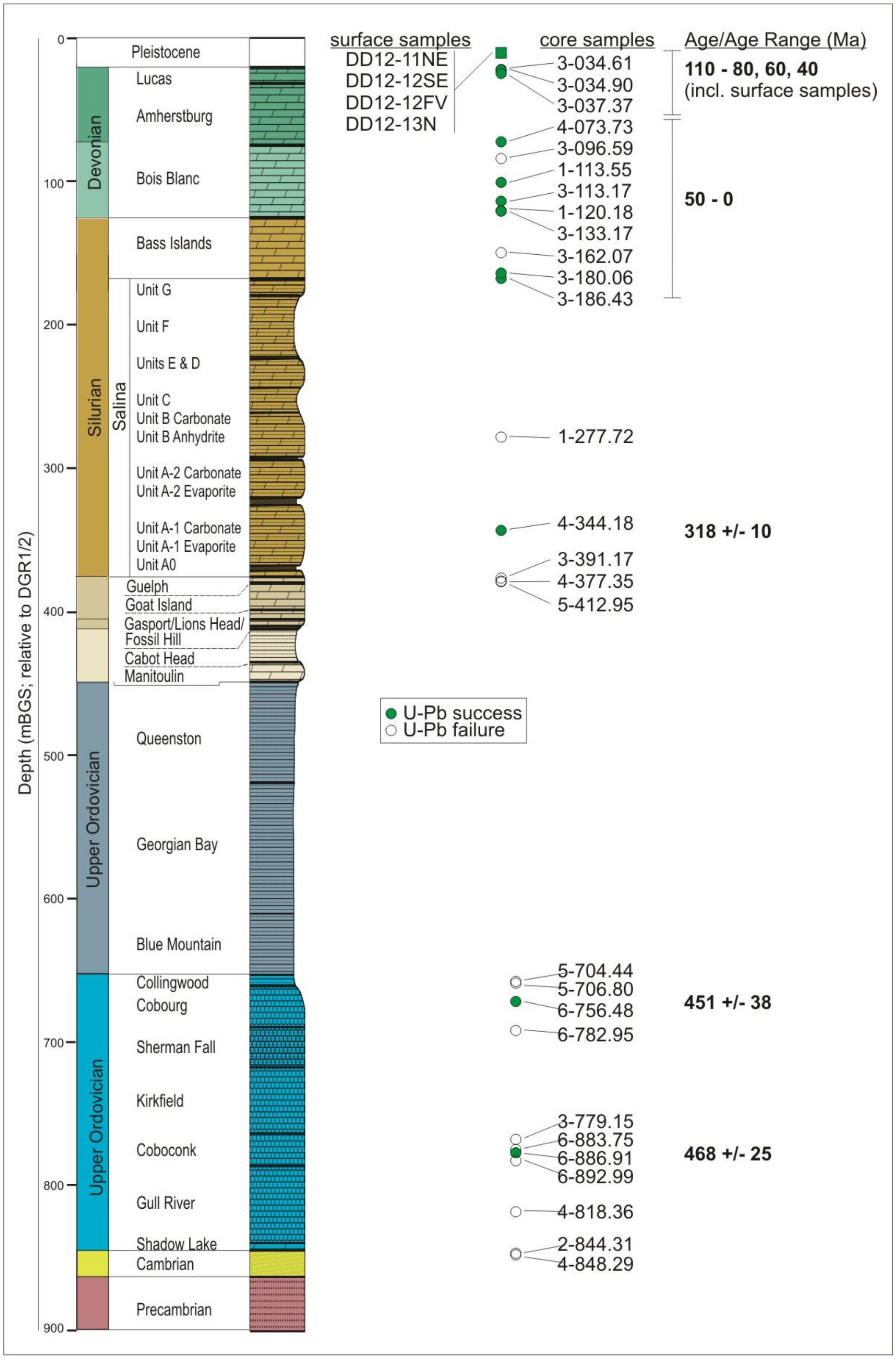


Figure 4-24: Sample Numbers, Locations and Ages Obtained In Relation to the Paleozoic Stratigraphy Beneath the Bruce Nuclear Site for Secondary Calcite Analysed by Davis Between 2013 and 2016 (Davis 2016). Samples for which U-Pb Geochronology was Successful are Green and Unsuccessful Samples are White

In summary, the reported results show that shallow stratigraphic levels (Devonian-Upper Silurian) preserve ca. 110 to near 0 Ma old secondary calcite. The youngest examples are located in proximity to a regional unconformity, at the top of the Upper Silurian Bass Islands Formation, which is part of a near-surface permeable carbonate aquifer system influenced repeatedly by glacial events during the latter half of the Pleistocene. A sample from the deepest Upper Silurian Salina A1 Unit yields a ca. 318 +/- 10 Ma calcite age. Rare datable calcite veins in Ordovician (Trenton and Black River groups) samples only record syn-depositional to diagenetic Paleozoic ages (451 +/- 38 Ma and 468 +/- 25 Ma).

Fluid inclusions trapped within the infilling minerals of rock cores (veins and vugs) during their growth and later deformation can provide representative samples of the chemical composition, density and temperature of ancient fluids (i.e., paleofluids). In collaboration with the University of Toronto studies summarized above, a fluid inclusion study at the University of Bern, involving petrographic examination of the vein and vug infilling mineral phase(s) from selected intervals within Bruce nuclear site cores, was completed in 2015 and the final report was submitted to the NWMO for publication in 2016 (Diamond et al. 2016). This collaborative approach between the University of Toronto and the University of Bern focused on evaluating the data for any meaningful interpretations about the timing of fluid movement in the sedimentary rocks at the Bruce nuclear site, as well as the nature (i.e., temperature and salinity) of the fluids. Additional work will be undertaken in 2017 focused on the characterization of vein, vug and fracture calcites found in Silurian-aged rock units from the Bruce nuclear site.

The University of Toronto is working collaboratively also with the University of Windsor on secondary mineral characterization (see Section 4.1.2.1). The University of Windsor has collected additional samples of secondary calcite and dolomite, which occur in small veins within the Cambrian bedrock as well as the Upper Ordovician carbonate rocks of the Trenton and Black River groups in southwest Ontario. Their source fluid(s) are characterized by fluid inclusion analysis and then provided to the University of Toronto for uranium-lead (U/Pb) geochronology. This collaborative approach is adding to the previous geochronological and stable isotope datasets, and contributing new trace-element geochemical data for the secondary minerals – all in an effort to improve confidence in the interpretation of the source fluid age and origin.

4.2.1.2 Evaluating Solute Mobility on Geologic Timescales

An integrative study (*Petts et al., to be submitted to Applied Geochemistry in 2017*), incorporating geochemical data from multiple work programs, was completed at the University of Ottawa. The purpose of the study was to assess the source and evolution of fluid migration in the secondary porosity of the low permeability Ordovician carbonates situated on the eastern flank of the Michigan Basin beneath the Bruce nuclear site. These carbonates comprise the Black River and Trenton Group limestones and dolostones at a nominal depth of 650 to 840 m below ground surface. The study focused on secondary mineral formation in the Cambrian and Ordovician sediments, and had three main components: 1) fluid inclusion analyses of fracture-hosted calcite at the University of Bern (see Section 4.2.1.1); 2) extensive C-, O- and Sr-isotopic characterization of secondary minerals in the Cambrian and Ordovician formations at the University of Ottawa (see Figure 4-25); and 3) integration of the fluid inclusion/geochemical data with the results of a successful U-Pb dating study (see Section 4.2.1.1) of fracture infill calcites by LA-ICP-MS and ID-TIMS at the Jack Slattery Geochronology Laboratory, University of Toronto.

The data was used to re-examine and refine a conceptual model for the fluid migration history in the 200 m thick Ordovician carbonate sequence, based on the presence of up to six identifiable fluid stages (see Figure 4-26). Key results of the integrated study indicate: 1) that multiple generations of secondary fracture minerals are evident in primary fluid inclusions, suggestive of episodic fluid migration events; 2) that secondary mineral formation reflects a mixed fluid origin (hydrothermal brines sourced from the underlying crystalline shield and/or from extensive fluid-rock interaction during transit in the Cambrian, as well as connate seawater); 3) U-Pb calcite fracture infill dates consistent with emplacement during the Upper Ordovician to Silurian time period (~450 to 435 Ma); and 4) little or no hydrogeochemical similarity between the overlying low-permeability Ordovician carbonates and underlying higher permeability Cambrian-Shadow Lake formations.

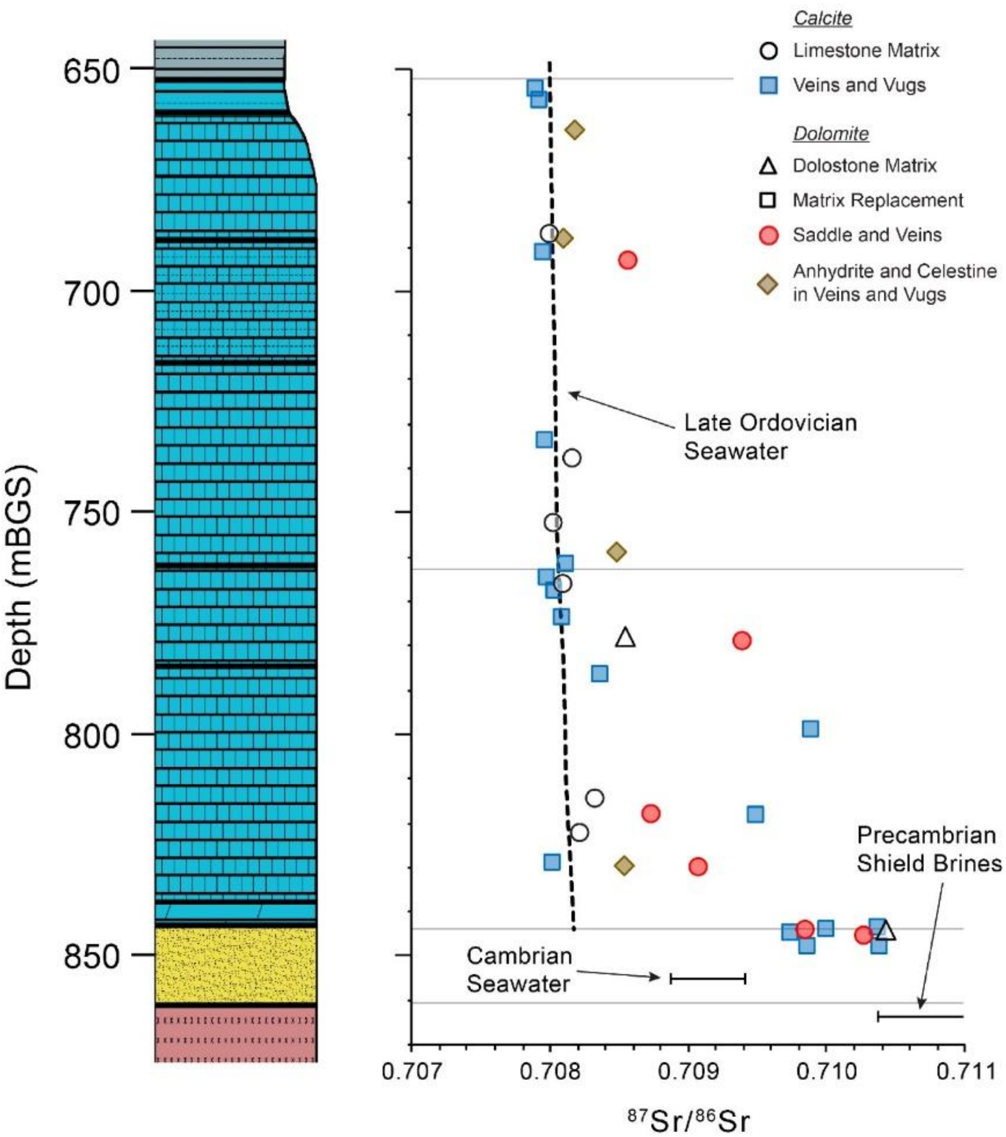


Figure 4-25: Strontium Isotope Data for Secondary Minerals in the Ordovician-Cambrian Sedimentary Rocks at the Bruce Site (*extracted from Petts et al., to be submitted to Applied Geochemistry in 2017*)

There was no evidence to suggest large-scale fluid migration through the Ordovician carbonates after the Silurian Period, despite evidence for orogeny-induced migration elsewhere in the Michigan Basin. This strongly suggests that the low permeabilities in the carbonates at the site (i.e., <10^{-11} m sec^{-1}) were established early in the evolution of the system. The overall findings of this integrative study support the long-standing conclusion that the deep sedimentary formations beneath the Bruce nuclear site comprise an aquiclude system, in which solute migration is diffusive, and effectively has been isolated from the shallow environment for hundreds of millions of years.

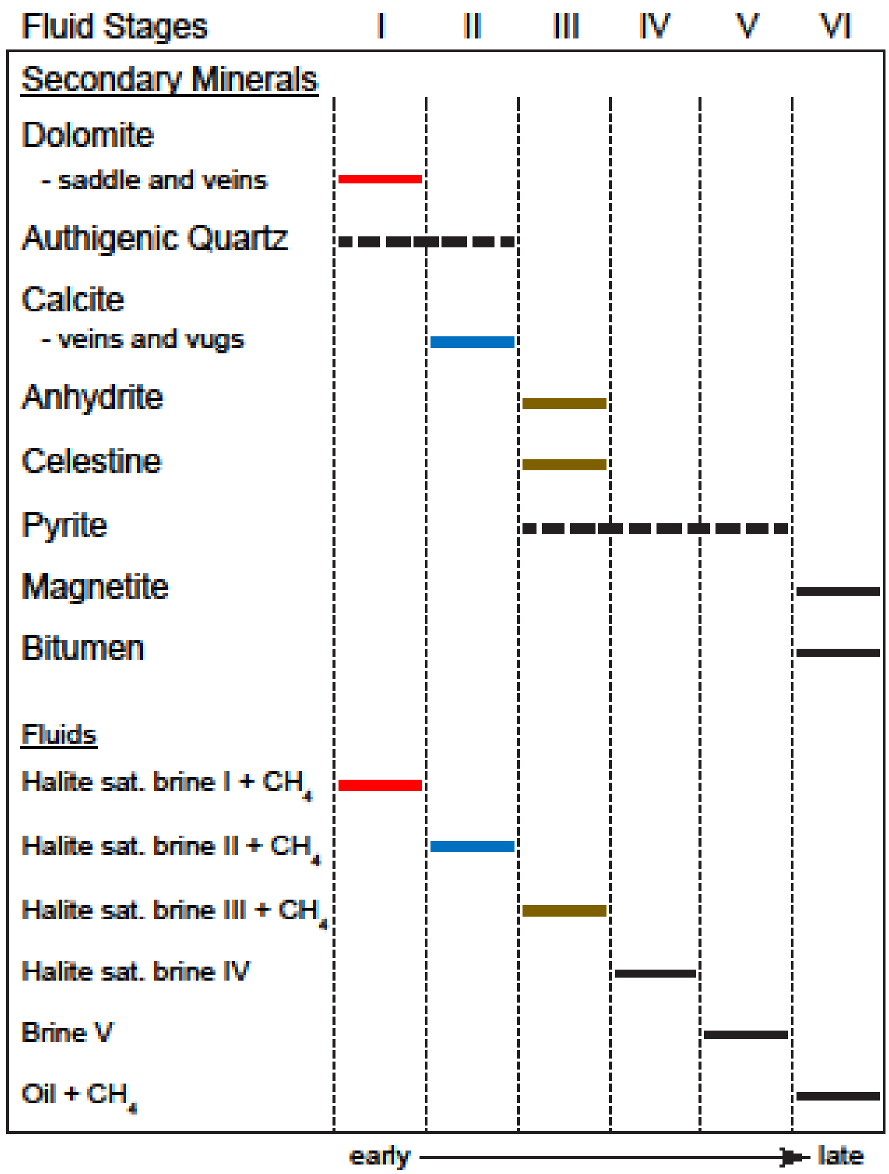


Figure 4-26: Fluid Inclusion Stages and Mineralogy (*from Petts et al., to be submitted to Applied Geochemistry in 2017*)

4.2.1.3 Glacial Perturbations - Glacial Systems Modelling

Over the last 900,000 years, the Canadian landmass has been subjected to nine glaciation events, each lasting for periods of approximately 100,000 years (Peltier 2002). Glaciation associated with long-term climate change is considered the strongest external perturbation to the geosphere at potential repository depths. Potential impacts of glacial cycles on a deep geological repository include: 1) increased stress at repository depth, caused by glacial loading; 2) penetration of permafrost to repository depth; 3) recharge of oxygenated glacial meltwater to repository depth; and 4) the generation of seismic events and reactivation of faults induced by glacial rebound following ice-sheet retreat. The ability to adequately predict surface boundary conditions during glaciation is an essential element in determining the full impact of glaciation on the safety and stability of a DGR site and will be a necessary component of site characterization activities. For the purpose of the NWMO's studies into the impact of glaciation, such boundary conditions have been defined based on the University of Toronto's Glacial Systems Model (GSM) predictions (Peltier 2002, 2006, Stuhne and Peltier 2015). The GSM is a state-of-the-art model used to describe the advance and retreat of the Laurentide ice-sheet over the North American continent during the Late Quaternary Period of Earth history.

The latest version of the University of Toronto GSM has been updated to adopt a new framework to honour observational constraints independently of ice-sheet dynamics. This includes a mass-balance adjustment to nudge the ice-sheet thickness solution towards the observationally validated ICE-6G model of glacial isostatic adjustments.

Nudging offers a more practical approach to leading-order data assimilation and error estimation than Bayesian calibration, which was employed in Peltier (2006). By nudging the new simulations towards ICE-6G, the extent to which ice-sheet dynamics are influenced by the much higher frequency temporal variability that is evident in ice core-based temperature inferences is limited. The updated GSM methodology has been validated with respect to the still-existing Greenland and Antarctic ice-sheets, and then applied to the generation of a dataset describing Canadian ice-sheets over the last 100,000 year glacial cycle. Included in this dataset are predictions of ice thickness, permafrost thickness, basal temperature, meltwater production, lake depth, and other two-dimensional, time-varying fields from a reference solution along with corresponding local error estimates. The ice-thickness field and corresponding error estimate at key times is illustrated in (Figure 4-27). The impact of parameter variability on ice-sheet dynamics was assessed through a suite of sensitivity analyses, with results indicating that variability in ice-sheet thickness associated with model parameter sensitivity is low in the interior of the ice-sheet (see Figure 4-28).

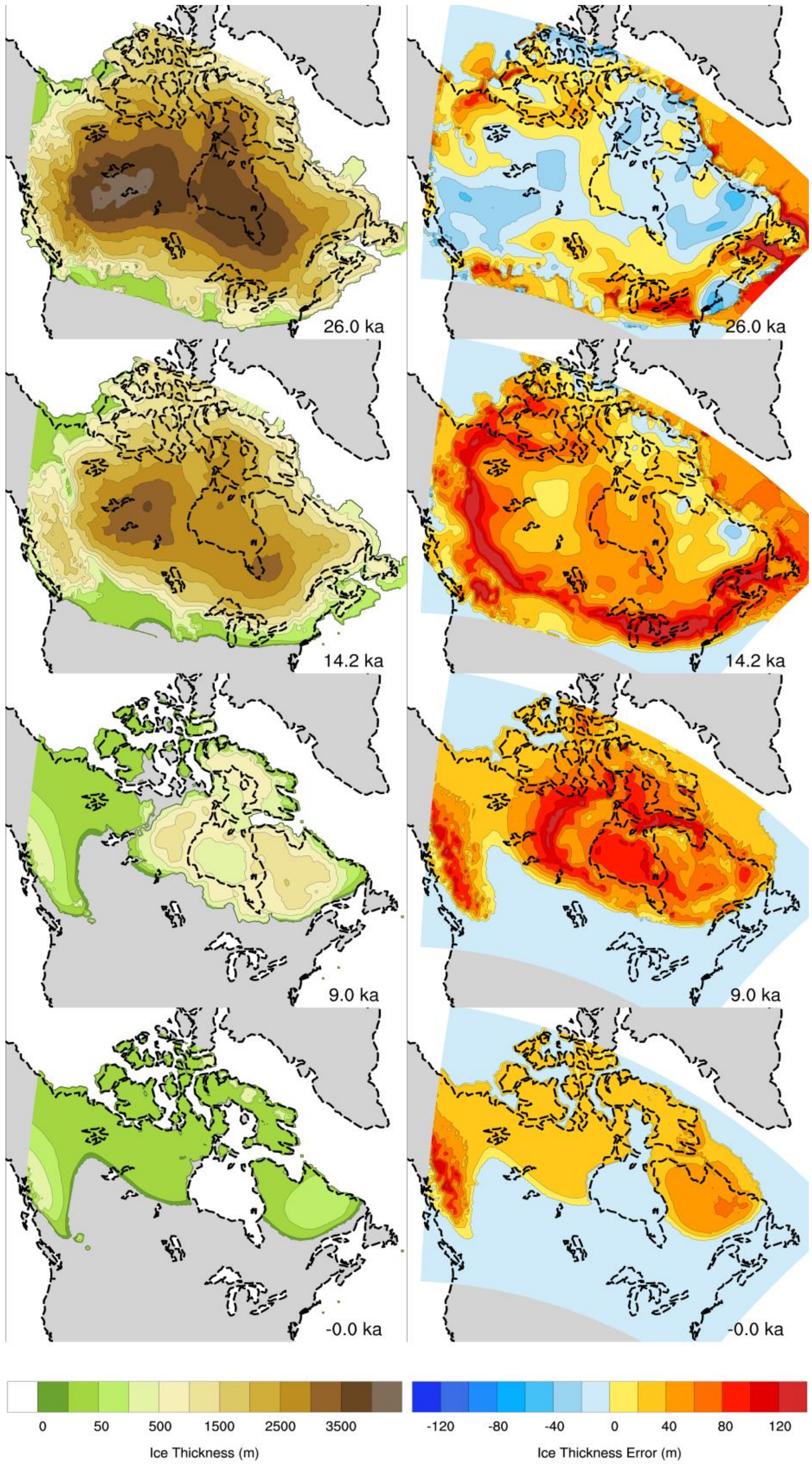


Figure 4-27: Reference Solution Ice Thickness, I (left), and Error, _I (right), at t = 26 kyr BP (LGM),14.2 kyr BP, 9 kyr BP, and Present

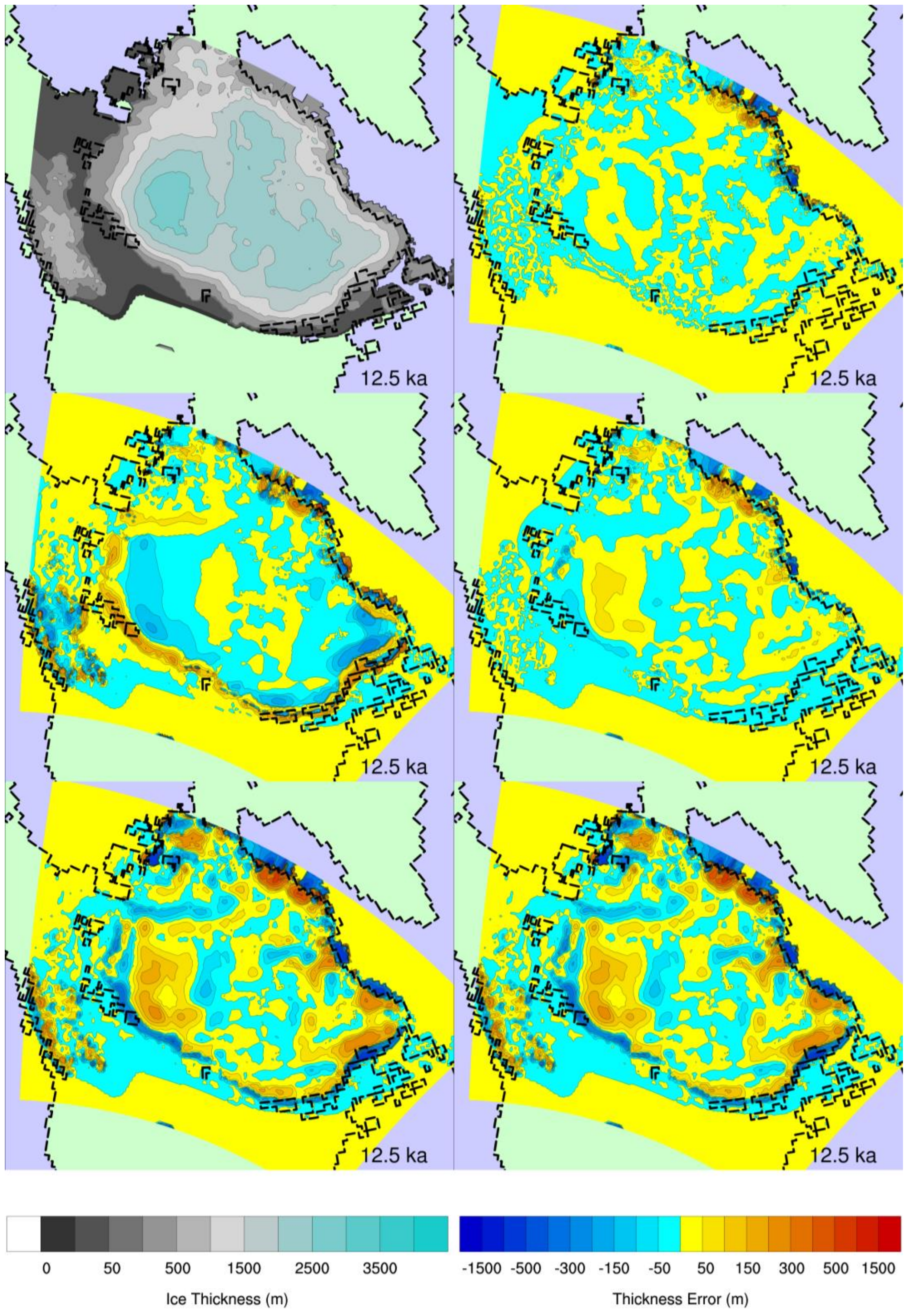


Figure 4-28: Variability of Ice Thickness with Respect to Shelfy-Stream-Based Ice Hardness Factor, Till Geometry Parameters, Shallow-Ice-Based Ice Hardness Factor, all Parameters, and a 10-Parameter Subset of the Full Parameter Ensemble

4.2.1.4 Groundwater System Evolution

NWMO continues to develop numerical methods to assess the long-term evolution of groundwater systems at depth over geologic timescales relevant to safety. Numerical methods are used to assemble and test descriptive geosphere conceptual models, which are developed from the integration of multidisciplinary data sets collected during site characterization activities. The development of numerical groundwater models during site characterization activities allows for the refinement of the understanding of groundwater system evolution in both crystalline Canadian Shield and sedimentary basin environments.

Research into the long-term behaviour of groundwater systems at depth were continued in 2016 at the University of Waterloo. Numerical methods to assess the long-term stability and evolution of groundwater systems in the fractured crystalline rock of the Canadian Shield at regional and sub-regional scales were refined. Performance measures used to assess groundwater system stability at potential repository depths include velocity magnitudes, Mean Life Expectancies (MLEs), and the depth of penetration of surficial recharge during glaciation. MLEs estimate the time it would take for a particle of water in a particular location to transit to the discharge location, and includes transport by advection and diffusion.

In crystalline rock, the presence of fracture zones will act to decrease the MLEs at repository depths, which would be associated with faster travel to surface (Figure 4-29). Areas of the rock mass not influenced by fracture zones will exhibit longer lived MLEs and would be associated with low rates of mass transport. The distribution of fracture zones in the model are developed using the fracture network modelling tool MoFrac (Section 4.1.4.4).

As illustrated through glacial systems modelling conducted by the University of Toronto (Section 4.2.1.3), glaciation is expected to be the single greatest external perturbation to the groundwater system at depth. The influence of glaciation on the groundwater systems is represented in the groundwater model through the application of paleohydrogeologic surface boundary conditions estimated for the Laurentide ice-sheet, which cover the previous 120,000 years. Although the conductive fracture zones permit the penetration of surficial recharge to depth, areas at potential repository depths remain free of tracer, which is indicative of low rates of mass transport (Figure 4-30). The rates of mass transport will be influenced in large part by the rock mass hydraulic conductivity.

The evolution of the groundwater system at repository depths can also be illustrated through plots of velocity magnitudes versus time (Figure 4-31). During the glacial advance and retreat, the velocity magnitudes for areas away from the influence of fracture zones maintain velocities on the order of 10^{-2} to 10^{-3} m/year.

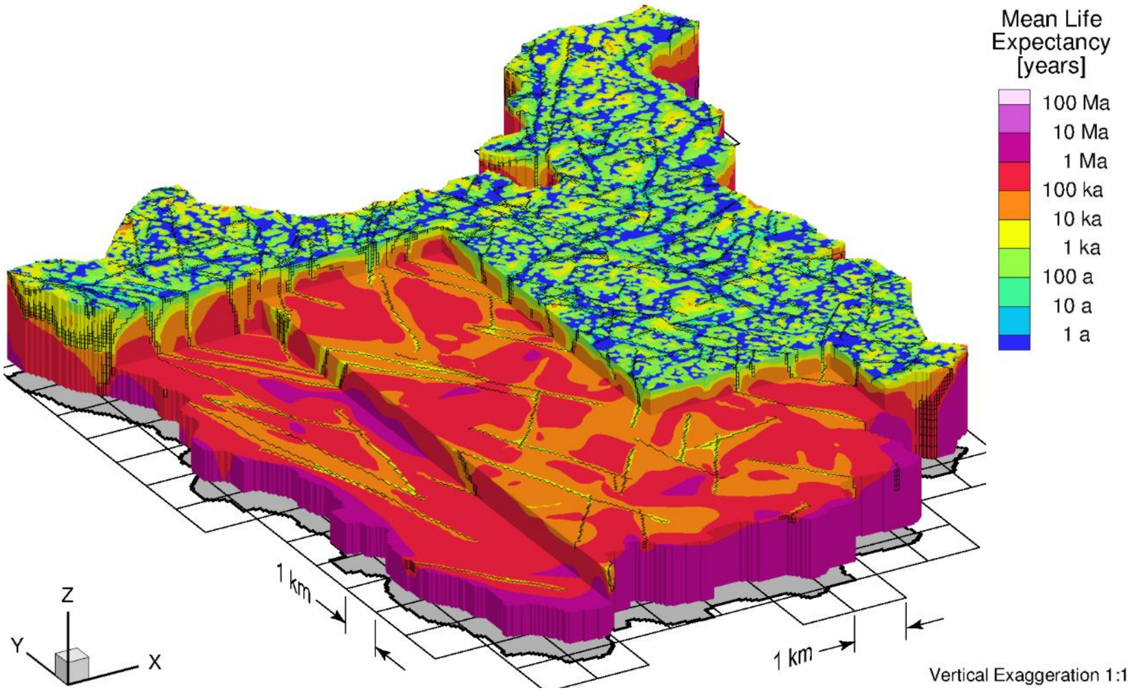


Figure 4-29: Mean Life Expectancies for a Hypothetical, Representative Crystalline Rock Geosphere

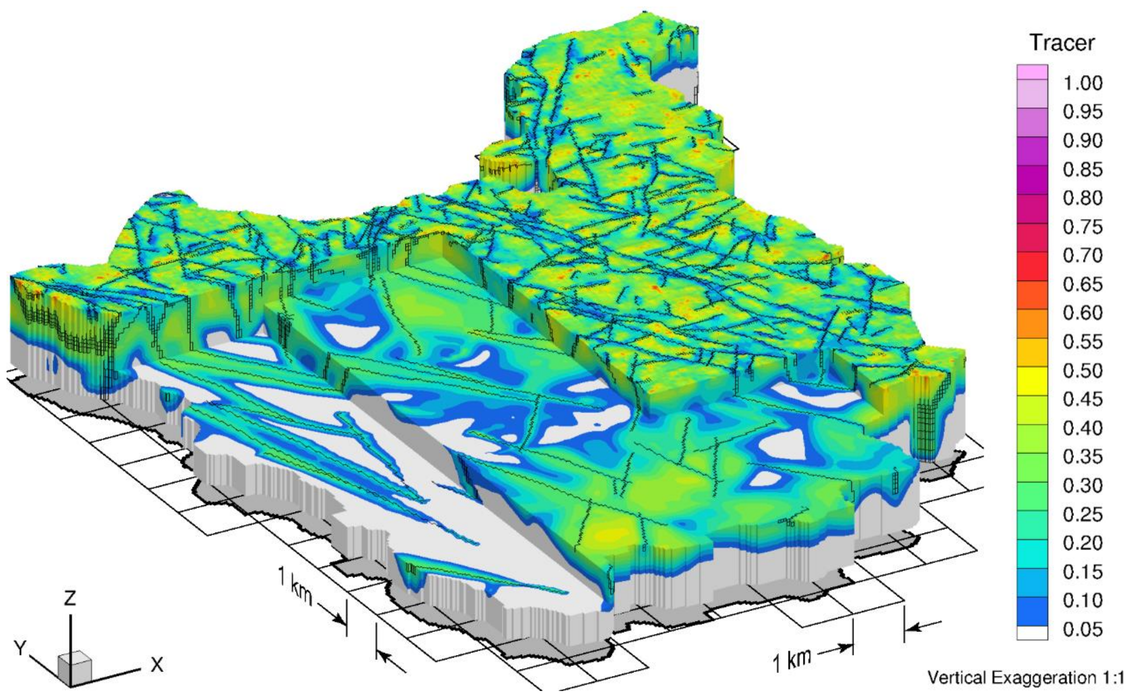


Figure 4-30: Tracer Migration After 120,000 Year Paleoclimate Analysis

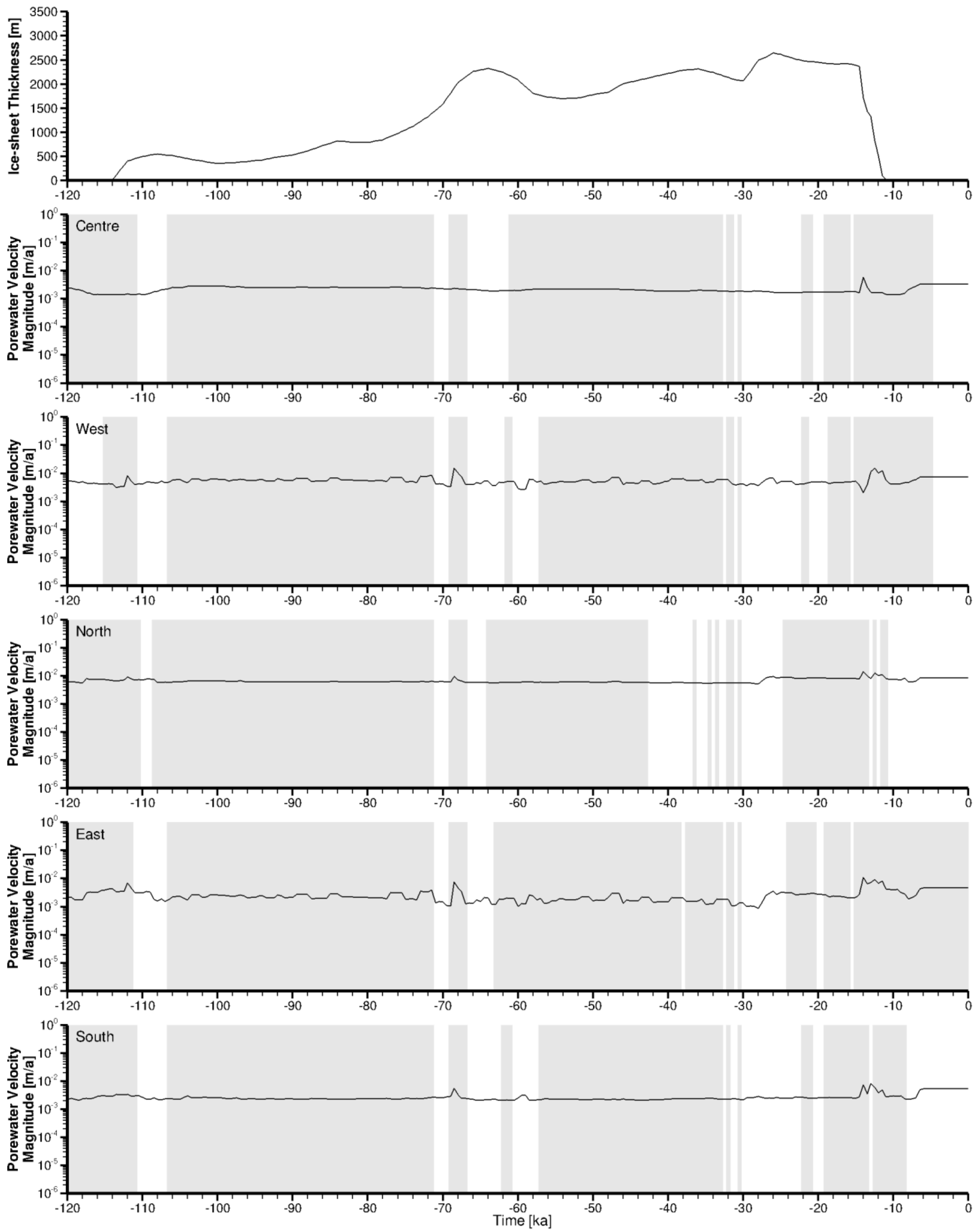


Figure 4-31: Velocity Magnitude versus Time for the Paleoclimate Boundary Conditions

4.2.2 Geomechanical Evolution

4.2.2.1 Fault Rupturing

When assessing the performance of a repository, fault rupture or reactivation could be a concern, as such activity might compromise the isolation potential of a repository for the migration of radionuclides. Seismicity within a crystalline shield environment is expected to be confined to regions containing pre-existing geological features (e.g., faults, fractures) within the rock mass. Damage to intact rock is unlikely to occur, because in-situ tectonic and glacially-induced stresses are not considered sufficient to generate the forces required to create new ruptures within intact rock (Lund 2006). However, there is evidence from the Scandinavian Shield that the effects of deglaciation on the lithosphere could lead to fault reactivation. An example of a reactivated fault is the Pärvie fault in northern Sweden, which displays offsets of up to 10 m over distances of 150 km (Kukkonen et al. 2010). Within the Canadian Shield, there is only one example of a modern earthquake being linked to surface rupture – the 1989 Ungava (Northern Quebec) M6.3 earthquake that displayed up to 3 m of offset at the surface, over a distance of 7 km (Adams 1989). There is currently no evidence for surface rupture within Ontario, and no identified structures that can be conclusively linked to postglacial reactivation (Fenton 1994).

A study of the regional seismic hazard of a hypothetical shield site in northwest Ontario reveals the likelihood of fault rupture – based on a moderate-to-large event, with rupturing at shallow depths – is extremely low. The probability of having a large enough seismic event that is sufficiently close to affect a deep geological repository, either through primary or secondary fault displacement or through strong motion, lies within the approximate range from nil to 5×10^{-7} per annum (Atkinson and McGuire 1993). Furthermore, because any proposed repository will be sited in an area away from known faults, the likelihood of reactivation is further reduced because it would require creating a new fault, likely as a result of fault propagation or extension.

Itasca Consultant Group conducted a numerical investigation to define the respect distance and the minimum distance between a seismogenic feature, such as a fault, and the repository. These analyses were based on the impact of a M6.1 seismic event and its effect on the deformation of the off-fault fractures along the repository horizon (Itasca 2017, in preparation). The main fault and the Discrete Fracture Network (DFN) fractures are represented explicitly as discontinuities in a three-dimensional distinct element model (Figure 4-32). The analysis follows the approach described by Fälth et al. (2016) and Fälth et al. (2015). The fault for the M6.1 event was modelled as a 10 km × 10 km planar area and the fractures were generated as disks according to the DFN characterization produced from the SKB (Svensk Kärnbränslehantering AB) Forsmark site (Le Goc and Darcel 2016). The dip of the analyzed fault was conservatively assumed to be 40°. Based on the compilation of available fault plane data of recent earthquakes in northern Ontario, the dips of these thrust-fault planes seem to be much steeper than those that caused events typically seen for western Quebec and Charlevoix, Quebec, at angles close to 60°.

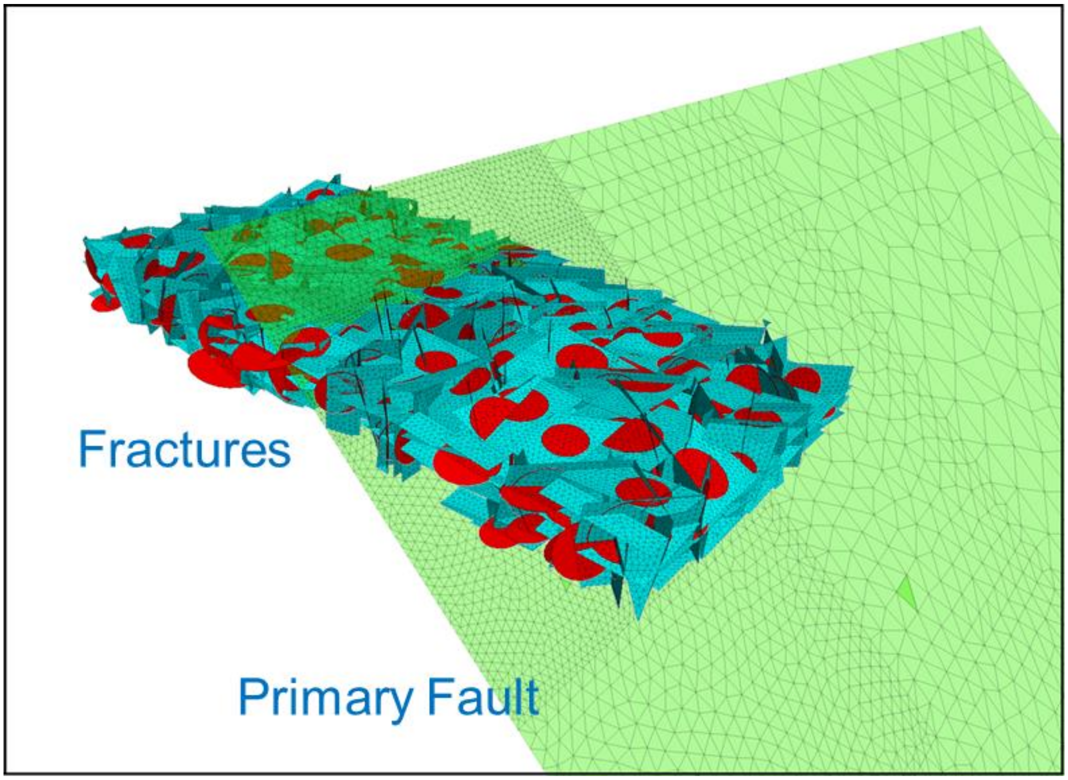


Figure 4-32: Fault Rupturing Model Showing a 40º Dipping Primary Fault and Discrete Fracture Network Along Repository Horizon

In the case of a M6.1 earthquake and a 40° dipping fault, five models with different DFN realizations predicted the maximum shear displacement along the fault to be approximately 3.8 m. This is inconsistent with the fault displacements reported by Wells and Coppersmith (1994) and Leonard (2014). Figure 4-33 shows a plan view of one of the fracture domains (DFN 001); red is used to indicate fractures that have been subjected to slips of > 5 cm, which corresponds to the design shear-capacity of an APM used fuel canister. The majority of fractures that slipped were located on the hanging wall side. Curves of cumulative distributions of shear displacements were also constructed to visualize the influence of the fracture distance from the fault plane. Figure 4-34 reveals the cumulative distribution curves of shear displacement for the incrementally increasing ranges of distance between the fracture centroid and a 40º dipping fault (Itasca 2017, in preparation).

Itasca (2015) examined the repository stability under a multiple glacial loading episodes scenario, as well as the peak thermal loading, in combination with rare seismic events. It was demonstrated that the relative differential deformation across the repository will not create any rupturing of the host and barrier rock, and thus would not adversely affect the performance of the repository.

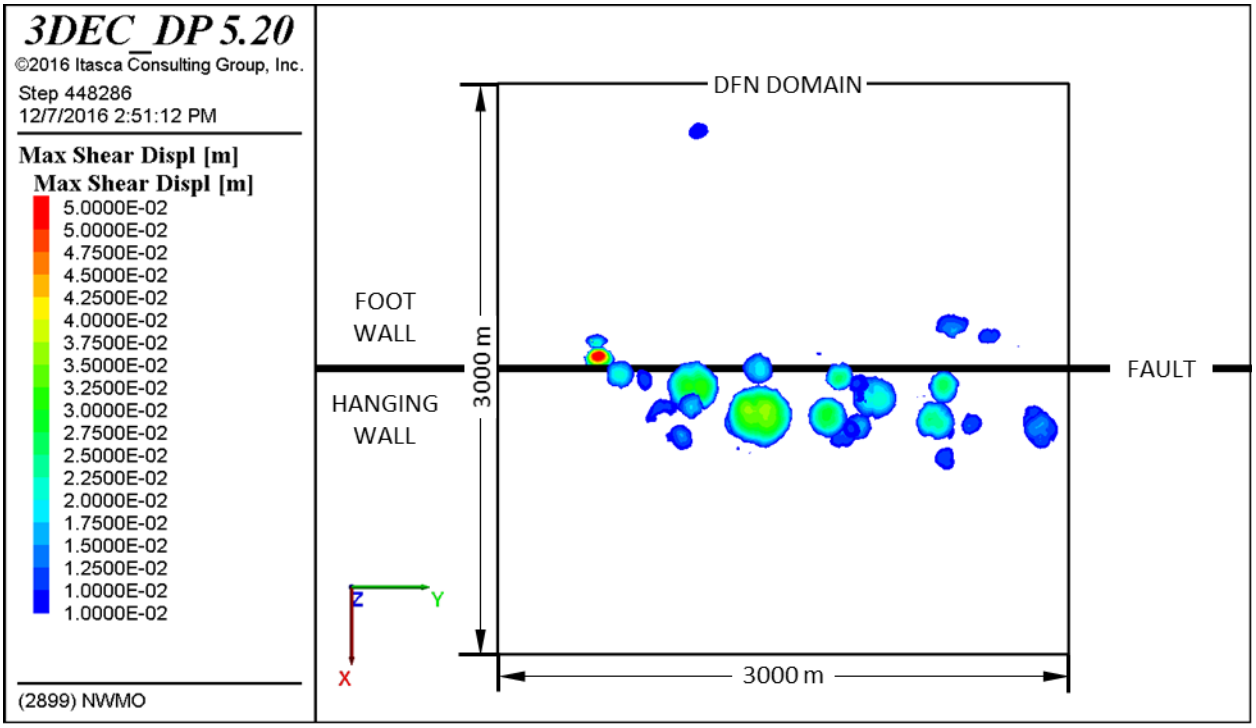


Figure 4-33: Fracture Shear Displacements in DFN 001. This Image Depicts a M6.1 Earthquake, with a 40° Dipping Fault. The Maximum Fracture Shear Displacement is 4.8 cm (fractures with shear displacement less than 1 cm are not shown)

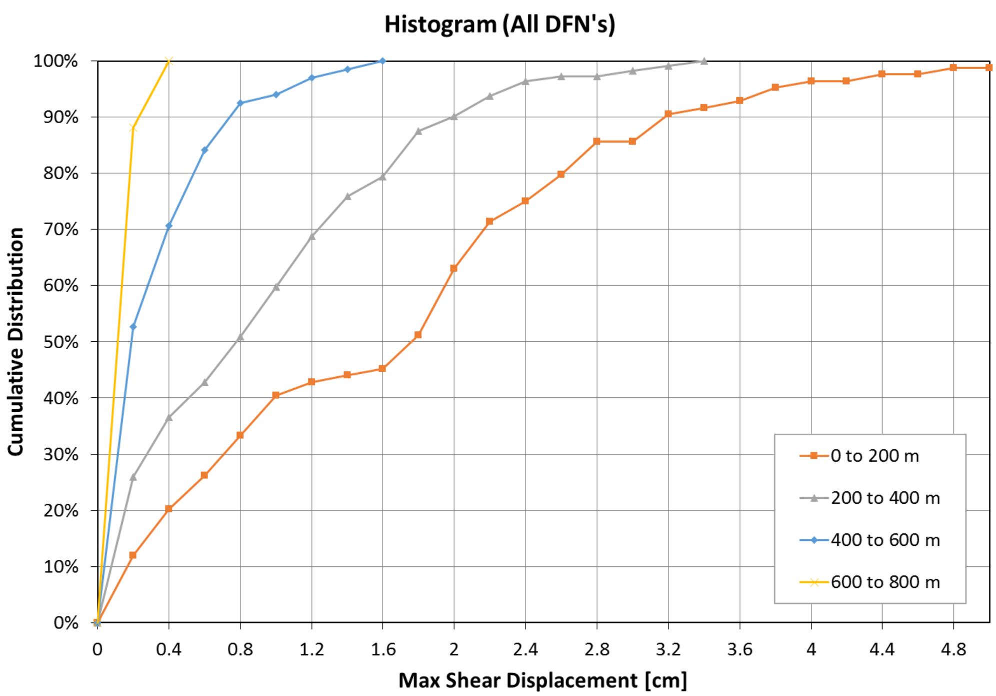


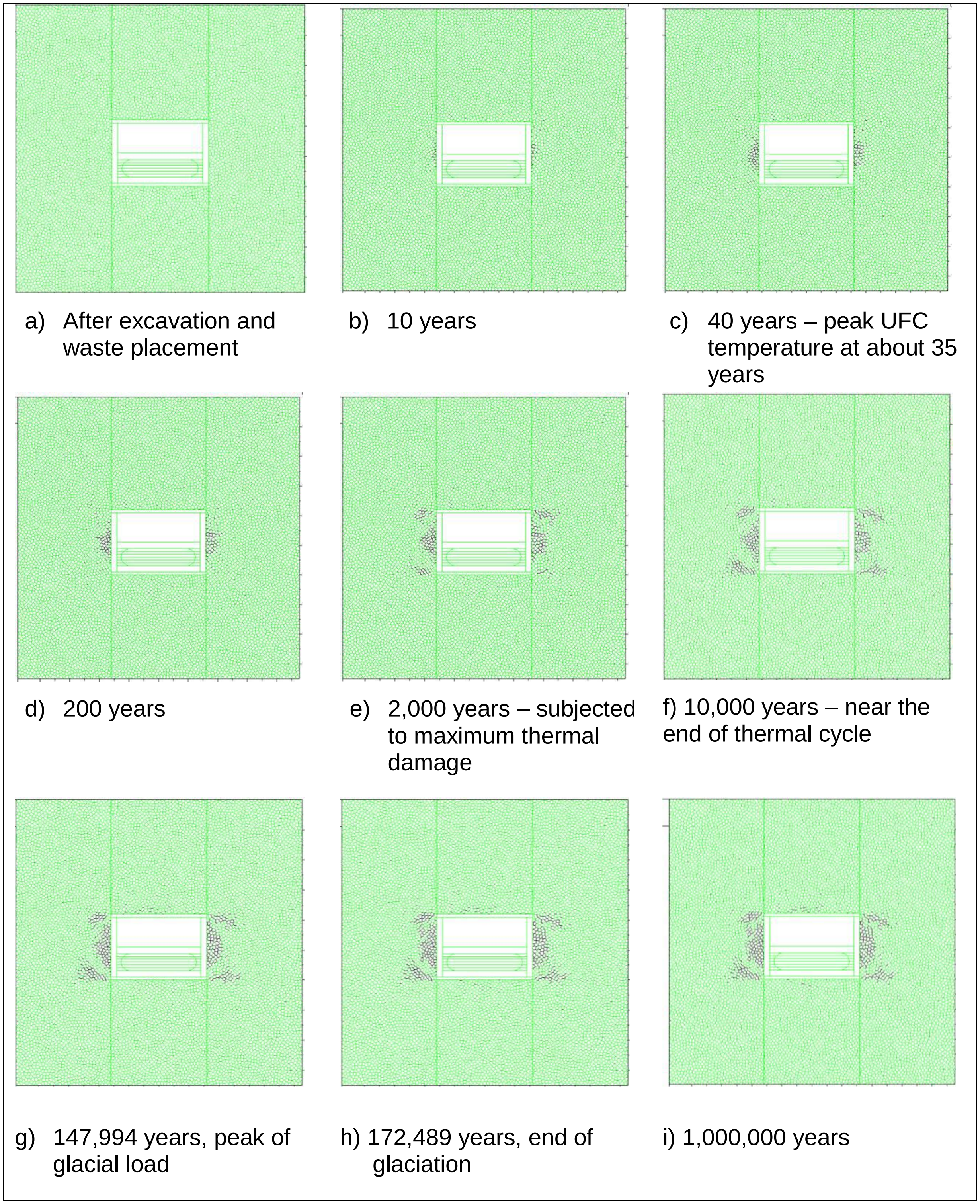
Figure 4-34: Cumulative Distributions of Shear Displacement For All DFNs For a Magnitude M6.1 Earthquake and a 40° Dipping Fault

4.2.2.2 Long-term Stability

The study (Itasca 2015 and 2015 ATR) of long-term stability of the NWMO APM deep geologic repository (DGR) for high-level nuclear waste demonstrates safe performance of the repositories for APM Mark II (48 bundles) canister design and repository configurations in both sedimentary and crystalline rock settings. In the study, thermo-hydro-mechanical (THM) analyses were conducted based on bounding assumptions (unfavorable from the perspective of stress and damage in the rock) regarding mechanical properties and modelling of the rock mass. Some simplifications in the analyses resulted in overestimation of the deformation and damage of the placement room opening. Subsequently, several fully coupled THM analyses were performed in 2016 to gain further insight on: 1) the effect of refinement by repeating some of the earlier (Itasca 2015) simulations with more realistic parameters, and 2) the sensitivity of the model predictions to some uncertain model input parameters.

In the 2016 study, fully coupled THM analyses (Itasca 2017) of a placement room in a crystalline setting were carried out. Figure 4-35 shows that the extent of damage is confined to the vicinity of the opening. Beyond 10,000 years, other than the damage (EDZ) created during the thermal loading cycle, there is no noticeable change in EDZ extent to 1 Ma (Figure 4-35g-i). In the analyses, extremely conservative assumptions on the long-term strength (40% of the rock mass UCS) was also assumed. The long-term reduction in strength of the granite rock mass, glacial ice loading, and rare seismic shaking have insignificant effect on room stability (i.e. resulting in relatively small incremental damage (Itasca 2015)).

The main reason for overall good performance of the placement rooms, and relatively small effect of low long-term strength, is the backfilling of the room. The backfill provides the confining pressure which prevents spalling of the rock and opening of the fractures, and significantly slows the time-dependent strength degradation/stress corrosion processes. The analyses reveal the majority of damage created was created due to heating as a result of the thermal output from the UFC. Up to peak temperature, which occurs before 35 years, the extent of damage is confined to the near vicinity of the opening, behind the surface of the room walls (Figure 4-35c). As heating progresses, fracturing of the rock mass around the room increases. The extent of the damage zone reaches approximately 1 m away from the room wall at the end of thermal cycle (Figure 4-35f) and remains approximately the same throughout the 1 Ma simulated time frame.



a) After excavation and waste placement

b) 10 years

c) 40 years – peak UFC temperature at about 35 years

d) 200 years

e) 2,000 years – subjected to maximum thermal damage

f) 10,000 years – near the end of thermal cycle

g) 147,994 years, peak of glacial load

h) 172,489 years, end of glaciation

i) 1,000,000 years

Note: (1) Black markings indicate microcrack/damage and (2) Placement room dimension: 3.2 m (W) x 2.2 m (H)

Figure 4-35: Evolution of Damage up to 1,000,000 Years

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 2016 to further this objective are described in the following sections.

The NWMO has completed studies that provide a technical summary of information on the safety of repositories located in a hypothetical crystalline Canadian Shield setting (NWMO 2012a) and the sedimentary rock of the Michigan Basin in southern Ontario (NWMO 2013). The reports summarize key aspects of the repository concept and explain why the repository concept is expected to be safe (see Table 5.1).

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

Repository depth provides isolation from human activities
Site low in natural resources
Durable wasteform
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. Most radionuclides are trapped within the UO_2 grains and are only released as the fuel itself dissolves (which in turn only occurs if the container fails). 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 corrosion of UO_2 under used fuel container conditions is important for long-term predictions of used fuel stability.

The 2016 program on UO_2 dissolution continued at Western University and included:

1. Validation of the model developed to determine the effect of H_2 on the corrosion rate of the fuel; and
2. Determination of the influence of rare earth doping on the behaviour of UO_2.

The results of the research undertaken at Western University are summarized in Sections 5.1.1.1 to 5.1.1.2.

5.1.1.1 Validation of Mechanistic Model of UO_2 Fuel Corrosion

Alpha-radiolysis of water is the dominant mechanism for used fuel dissolution inside a failed used fuel container, with the alpha-radiolysis product H_2O_2 being the major fuel oxidant. For this reason, the influence of the alpha-dose rate on corrosion of UO_2 materials has been extensively studied (Poinssot et al. 2005). Measurements have been made on a wide variety of specimens including U-233 doped UO_2, Pu-238 doped UO_2, Ac-225 doped UO_2, UO_2 fuel pellets, SIMFUEL and some spent fuel. Although there is wide variability in the measured corrosion/dissolution rates (see Figure 5-1), a clear trend of increasing corrosion rate with increasing alpha-dose rate is apparent. A specific activity threshold below which the corrosion rate becomes independent of the alpha-dose rate has also been proposed; if such a threshold exists, Figure 5-1 suggests that it would be in the range 0.1 to 1 MBq/gUO_2.

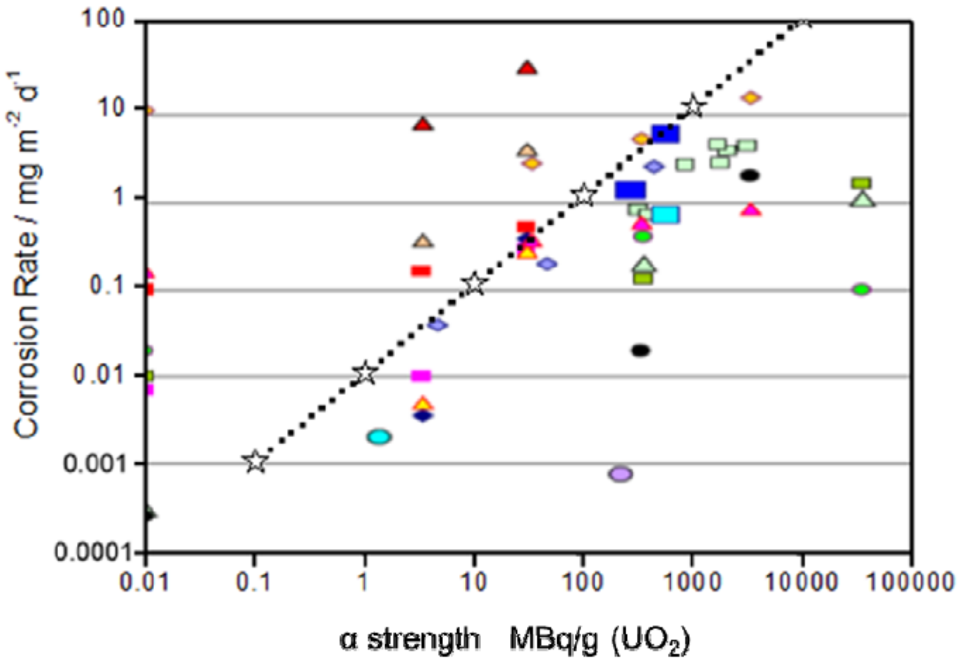


Figure 5-1: Comparison of Experimental Corrosion Rates from Poinssot et al. (2005) with Model Simulation Results (stars)

Recently, the fuel dissolution model developed to calculate the rate of fuel corrosion (Wu et al. 2014a, 2014b) was modified to ascertain the importance of radiolytic H_2 in suppressing fuel dissolution in a failed container for used fuel (Liu et al. 2016a, 2016b). Modelling results indicate that, for CANDU fuel with moderate burnup, only µM concentrations of H_2 are required to suppress corrosion of the fuel to negligible levels. In order to validate this model, it was used to determine the effect of the alpha-dose rate (or alpha-activity) on fuel corrosion (Liu 2017). The model simulations yield steady state corrosion rates for UO_2 fuel after a short initial period. The results, which are shown in Figure 5-1, are in good agreement with published experimental data, except perhaps for alpha-source strengths greater than 10^4 MBq/gUO_2. The rates measured at the highest alpha-source strength were measured on Pu-238 doped specimens and it has been suggested, but not proven, that the low rates indicate a stabilizing influence of Pu on the UO_2 matrix (features not incorporated into the model).

The good agreement between the model calculations and the measured dissolution rates (see Figure 5-1) helps to validate the model and, thereby, supports the model predictions that small concentrations of H_2 are sufficient to suppress fuel dissolution in a failed container (Liu 2017, Liu et al. 2016b).

5.1.1.2 Influence of Rare Earth Doping on the Behaviour of UO_2

The reactivity of UO_2 fuel and how it is modified by in-reactor irradiation is important in determining fuel corrosion rates. The key changes likely to influence the reactivity of the fuel are rare earth doping of the matrix, the presence of noble metal particles, and the development of non-stoichiometry (Razdan and Shoesmith 2014a, 2014b; He et al. 2012, 2007).

The suppression of the electrochemical reactivity of UO_2 by rare earth (RE^{III}) doping has been demonstrated by Razdan and Shoesmith (2014a, 2014b). This reduced reactivity was attributed to formation of RE^{III}-O_v clusters (where O_v represents an oxygen vacancy) accompanied by a contraction of the lattice. These studies were conducted on highly doped Gd (6 wt%) and Dy (12.9 wt%) UO_2. More recent studies have been carried out on a series of stoichiometric Gd-doped UO_2 materials, i.e., $(U_{1-y}Gd_y)O_2$ materials with y = 0.0, 0.01, 0.03, 0.05, 0.07 and 0.10 (Liu 2017).

The stoichiometric $(U_{1-y}Gd_y)O_2$ materials were synthesized, and characterized by X-ray diffraction (XRD) and Raman spectroscopy. The reactivity of the $(U_{1-y}Gd_y)O_2$ materials was investigated electrochemically in solutions containing carbonate and bicarbonate. Cyclic voltammetry and potentiostatic polarization curves were recorded. These experiments indicated that the reactivity of the materials was insensitive to the doping level for potentials (versus the standard hydrogen electrode) less than 0.1 V. At higher potentials, the reactivity decreased with doping level only for the highest doping levels ($y > 0.05$).

Figure 5-2 shows the total potentiostatic current (which is a measure of the reactivity of the material) measured over the one-hour duration of the experiments. For anodic oxidation at 0.1 V, there is no observable influence of Gd content on the total charge. At higher potentials, when dissolution as $UO_2(CO_3)_2^{2-}$ is occurring, the charge increases slightly over the doping range 0.01 to 0.05 and then decreases with y at higher doping levels ($y > 0.05$). However, overall the increase in doping does not exert a major effect on reactivity.

These effects can be interpreted on the basis of the XRD and Raman spectroscopic observations (Liu 2017). The XRD data shows that an increase in the doping levels leads to a contraction of the UO_2 lattice. This would be expected to inhibit the incorporation of O^{II} ions into the interstitial sites in the UO_2 fluorite lattice, thereby inhibiting the oxidation process. By contrast, an increase in the Gd^{III} content should lead to an increase in the number of oxygen vacancies, i.e., replacement of the U^{IV} ions with Gd^{III} ions requires further ionization of the remaining uranium ions (to U^V) or the creation of oxygen vacancies to maintain overall charge balance. The increase in the number of oxygen vacancies should increase the rate of oxidation by providing additional sites for the inclusion of interstitial oxygen. The changes in the current and charge with Gd content (Figure 5-2) suggest a competition between these two effects.

Experiments are also being carried out on hyperstoichiometric $(U_{1-y}Gd_y)O_{2+x}$. Initial results indicate that the highest reactivity is observed for the least Gd-doped material, as observed previously (He et al. 2009, 2007). As the Gd content is increased, the electrochemical reactivity decreases to values observed for the similarly doped stoichiometric specimens. This loss of reactivity with increased Gd content can be attributed to the elimination of available O_v due to the formation of Gd^{III}-O_v clusters, which leads to a significant lattice contraction; any enhanced reactivity due to hyperstoichiometry is overwhelmed by this contraction.

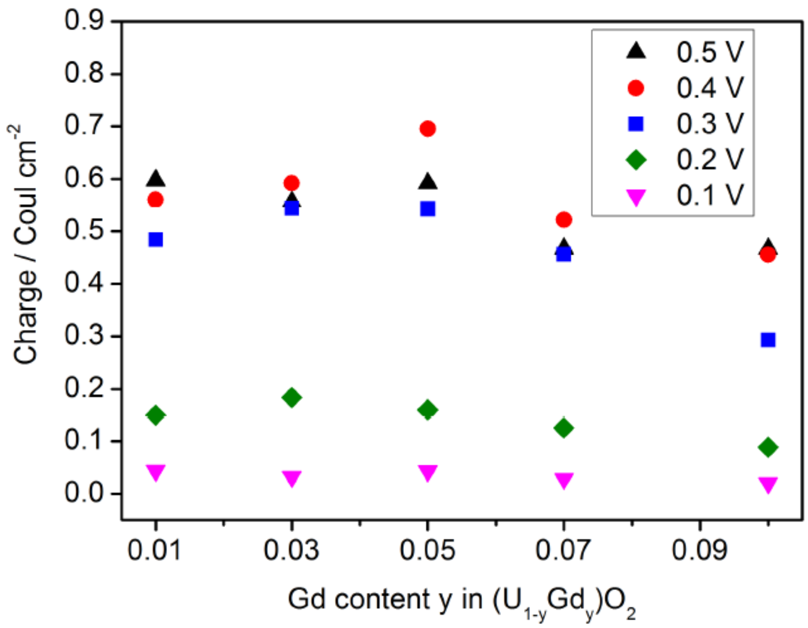


Figure 5-2: Total Anodic Charge Obtained by Integrating Current Measured Potentiostatically for One Hour on $(U_{1-y}Gd_y)O_2$ Electrodes at Different Potential in Solution Containing 0.05 mol/L Carbonate/ Bicarbonate

5.1.2 Near-Field 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 3.2.4.

5.1.2.1 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 V of the Thermodynamic Database (TDB) Project, which started in 2014, is nearing completion and planning for Phase VI of the project has commenced. Draft reviews of the thermodynamic data for iron (Volume 2), molybdenum, and auxiliary data have been prepared and should be finalized by the end of 2017. A draft report has been prepared on an update of the actinide and technetium thermodynamic databases and draft state-of-the-art reports have been prepared on the thermodynamics of cement materials and high-ionic strength systems. These latter reports will be published in 2018.

The NEA TDB project provides high-quality datasets. This information is important, but is not sufficient on its own, as it does not address the full range of conditions of interest. For example, the NEA TDB project has focused on low-salinity systems in which activity corrections are described using Specific Ion Interaction Theory (SIT) parameters. Due to the high salinity of groundwaters and porewaters observed in some deep-seated sedimentary and crystalline rocks in Canada, a thermodynamic database including Pitzer ion interaction parameters is needed for radionuclide solubility calculations.

For high-salinity systems, the THEREDA (THErmodynamic REference DAtabase) Pitzer thermodynamic database (Altmaier et al. 2011) is a relevant public database. It has been assessed by the NWMO and found to provide a good representation of experimental data for many subsystems. Therefore, the THEREDA database will be adopted by the NWMO for future work in high-salinity systems.

The NWMO is also co-sponsoring the NSERC/UNENE Senior Industrial Research Chair in High Temperature Aqueous Chemistry at the University of Guelph, where there is capability to carry out various thermodynamic measurements at high temperatures and high salinities. This Chair program initiated in April 2016. New equipment needed to carry out experiments of interest to the NWMO has been purchased and progress has been made in several areas (e.g., high-temperature heat capacities of antimony complexes).

5.1.2.2 Gas-Permeable Seal Test

The purpose of a gas-permeable seal is to enhance gas transport through the backfilled excavations of a 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 full-scale Gas-Permeable Seal Test (GAST) was constructed at the Grimsel Test Site. The NWMO is participating in this in-situ experiment and will be involved in the modelling of the Thermal-Hydro-Mechanical behaviour. Presently, the experimental facility is still in the saturation phase.

5.1.2.3 Shaft Seal Properties

The shaft seal for a deep geological 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 2016, NWMO continued with a series of basic physical and mechanical tests on 70/30 bentonite-sand shaft seal material and 100% MX-80 bentonite in order to establish the effect of groundwater salinity on their behaviour. The pore fluids are defined in reference to total dissolved solids (TDS) concentrations: deionized water, approximately 11 g/L TDS, approximately 223 g/L TDS, and approximately 335 g/L TDS.

The tests evaluate the following:

1. Compaction/fabrication properties of the materials (to Modified Proctor density);
2. Consistency limits (Atterberg Limits) and free swell tests;
3. Density of as-fabricated material;
4. Moisture content of as-fabricated material;
5. Mineralogical/chemical composition, including three independent measurements of montmorillonite content using different laboratories;
6. Swelling pressure;
7. Saturated hydraulic conductivity;
8. Two-phase gas/water properties, specifically the capillary pressure function (or soil-water characteristic curve, SWCC) and relative permeability function, measured over a range of saturations that include the as-fabricated and fully-saturated condition;
9. Mineralogical/chemical composition of the materials exposed to brine for an extended period of time;
10. Thermal properties including thermal conductivity and specific heat capacity; and
11. Mechanical parameters including Shear Modulus (G), Bulk Modulus (K) and Young's Modulus (E).

Testing for items 1 to 10 has been completed and measurements are consistent with anticipated values, based on literature information available for similar materials.

In 2014, the NWMO completed an initial series of basic physical and mechanical tests on the LHHPC and asphalt-based materials to establish baseline properties and also to determine the effect of high groundwater salinity on their behaviour. Tests on the LHHPC and asphalt–based materials were carried out using distilled water and water with a salinity of 270 g/L. The test results indicate that the LHHPC and asphalt-based samples have very low porosity and very low saturated hydraulic conductivity (< 10^{-13} m/s) under these two reference conditions. Figure 5-3 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.

Optimization of the LHHPC formulation started in late 2015. Some concrete ingredients in the original 1990's reference formulation (e.g., super-plasticizer and speciality cement) may no longer be commercially available, so alternative formulations are being prepared that use ingredients from local and sustainable sources. Trial mixes were prepared and assessed for initial optimization on 7-day and 28-day compressive strength and on results from slump/slump flow tests. Further optimization of production mixes are on-going and will be based on key performance parameters such as slump/slump flow, unconfined compressive strength, temperature rise, shrinkage rate, density, porosity, pH, and saturated hydraulic conductivity. Interim results were presented by Aldea et al. (2016). The performance of the final optimized mixes will be similar to, or exceeding, the original reference formulation.

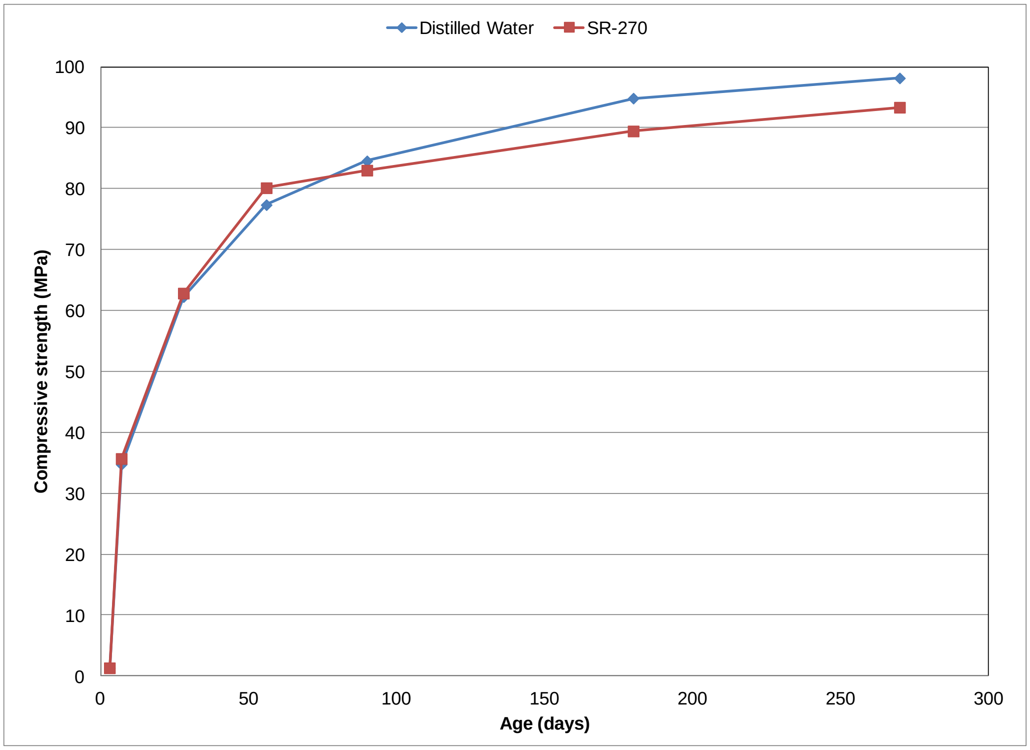


Figure 5-3: Unconfined Compressive Strength Results for LHHPC

5.1.2.4 Thermal Performance of a Repository in Crystalline Host Rock

The NWMO is assessing the safety performance of the Mark II Engineered Barrier System. In this design, a Mark II Used Fuel Container is placed in a “buffer box” made of highly compacted bentonite, which is then placed and sealed in an underground room. Guo (2016a) describes the thermal performance of a conceptual deep geological repository involving the Mark II container and placement concept in a hypothetical crystalline rock environment.

A series of design studies for conceptual DGRs has been carried out over the past 30 years. These studies include two- and three-dimensional thermal transient and thermo-mechanical analyses. For numerical reasons, they are divided into far-field modelling and near-field modelling. In the Near-Field Models, an adiabatic thermal condition is applied on the four vertical outside boundaries, and as such, this represents a repository with an infinite horizontal dimension. The results from such models are known to be accurate at early times, with the thermal response overestimated at longer times.

To examine the influence of this boundary condition, thermal near-field modelling is performed for the Mark II repository using COMSOL and a method is proposed to account for boundary condition influences. The method is validated by comparing the modified COMSOL results with a theoretical solution produced using HOTROK. A great portion of the temperature change at later times in the non-modified near-field modelling results is attributed to the effect of the adiabatic condition applied on the four vertical boundaries (Figure 5-4 and Figure 5-5).

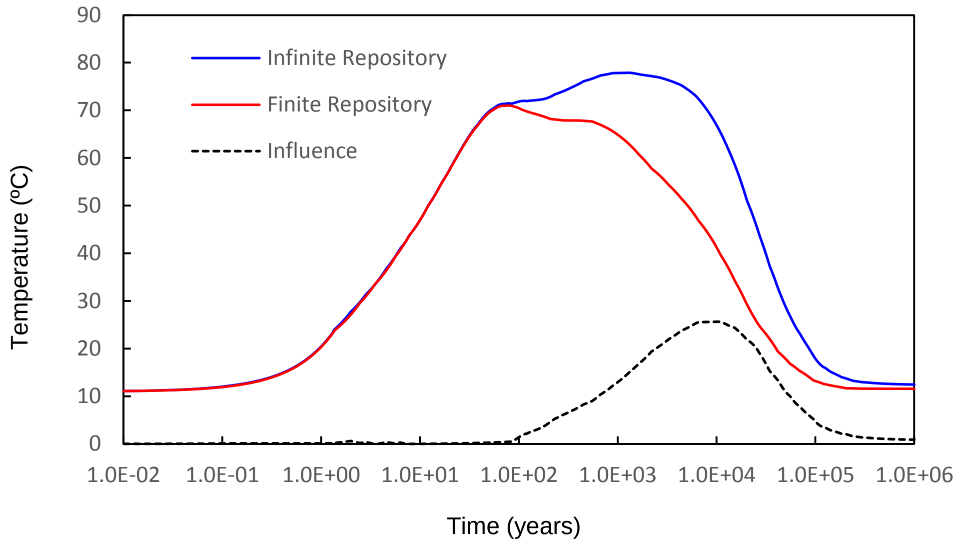


Figure 5-4: Temperature at Panel Centre from the Far-field Model with Horizontally Finite-Dimensional Repository and Temperature at Repository Depth from the Simplified Near-Field Model and their Differences

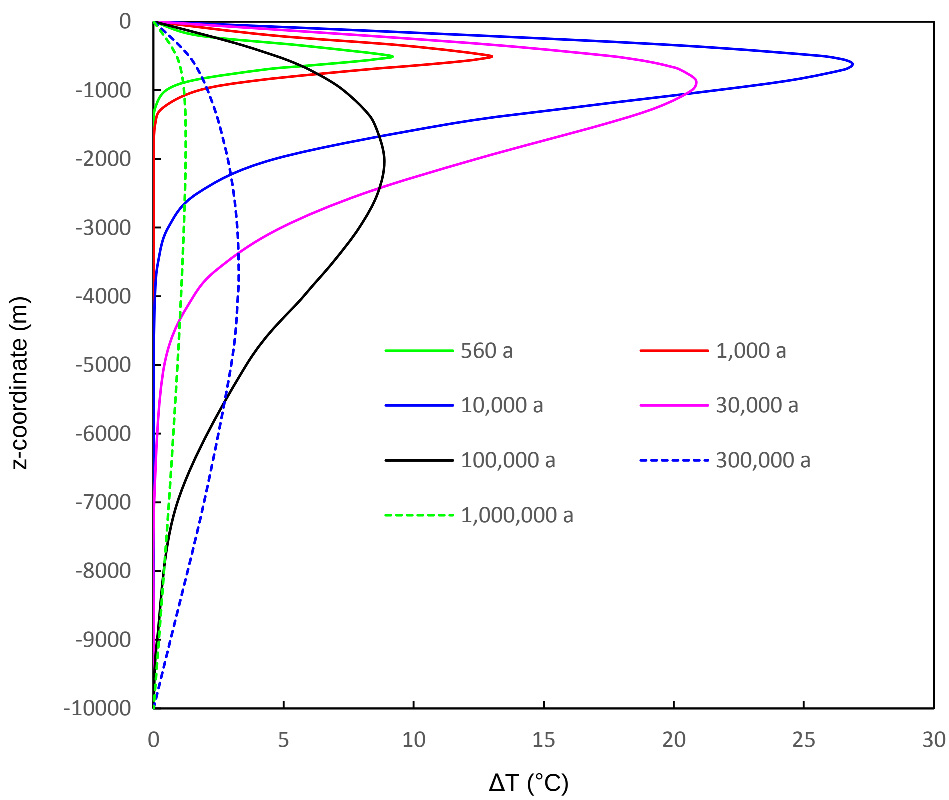


Figure 5-5: Temperature Difference Profiles along Vertical Line through Panel Centre between the Simplified Near-Field Model and the Far-field Model

The modified analysis shows that the thermal peak occurs early in the life of the repository and there is no comparable second peak after thousands of years for the case described in this report (Figure 5-6). For the case evaluated, the maximum container surface temperature is 84°C, occurring after 45 years (Figure 5-7), and the maximum temperature of the room centre between two containers is 83°C, also occurring after 45 years.

Below a depth of 4,000 m below ground surface, there is no influence of heat source or the adiabatic boundary condition used in the Near-Field Model after 10,000 years. After 100,000 years, although the influence of the adiabatic boundary condition can reach a depth of 8,000 m below ground surface, the influence of the heat source only reaches a depth of 4,000 m below ground surface (Figure 5-8).

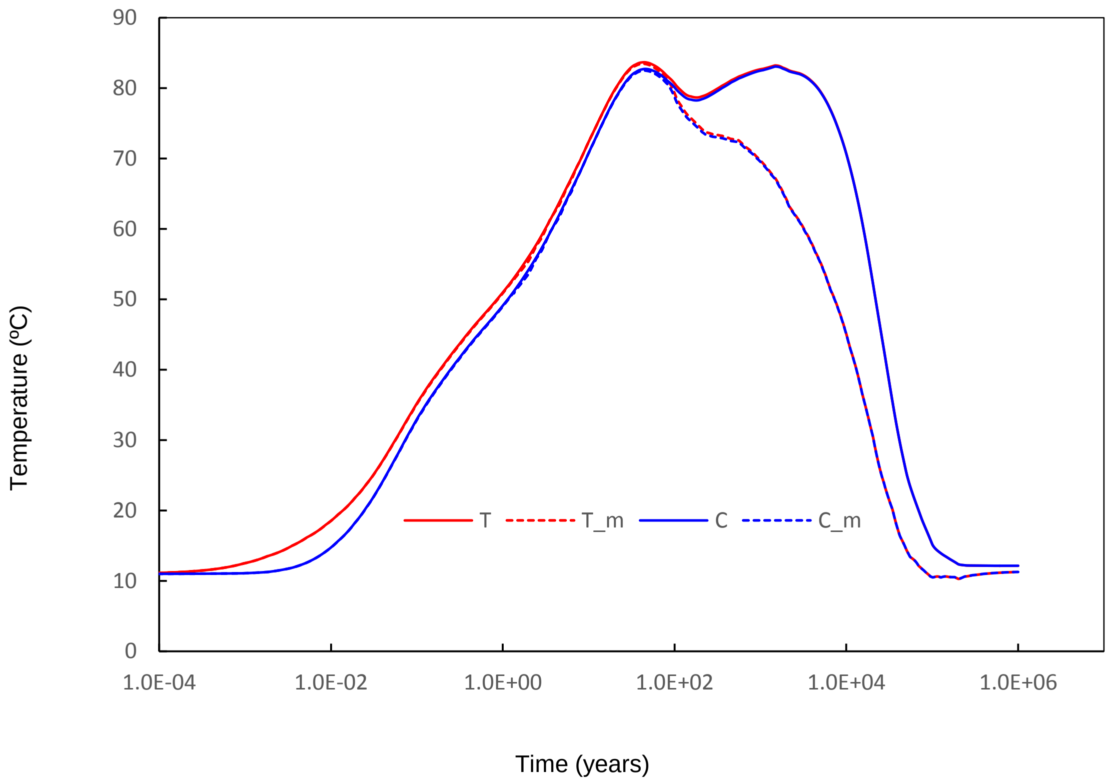


Figure 5-6: Comparison of the Temperature as a Function of Time at Point T (container surface) and Point C (centre of tunnel) between Near-Field Modelling Results and Modified Results

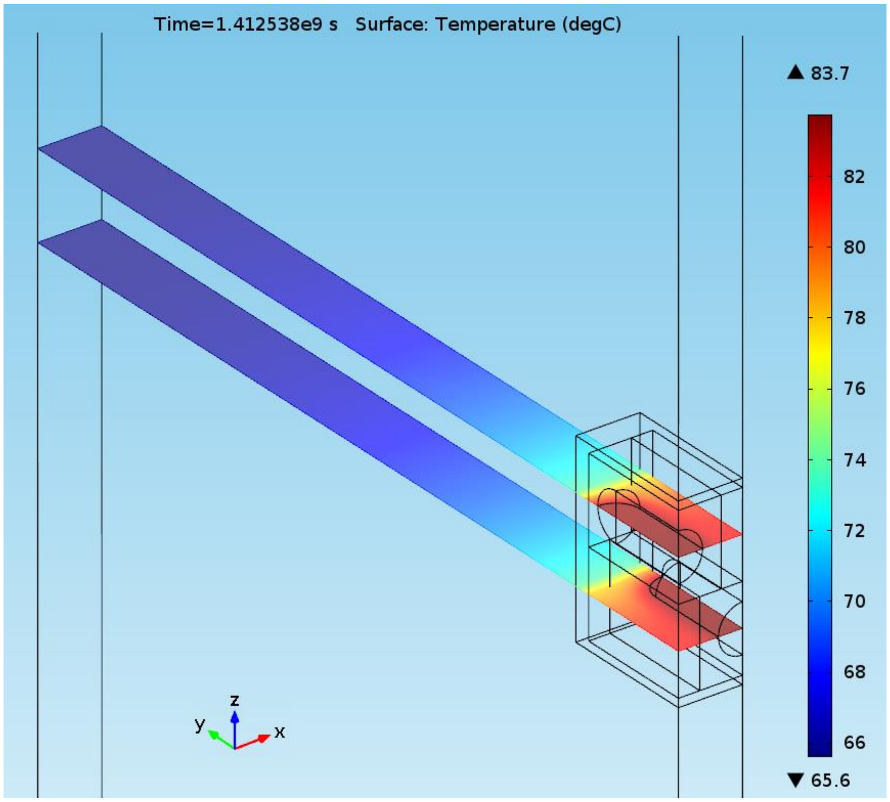


Figure 5-7: Temperatures in the Rock along the Horizontal Cross-sections Through the Container Axis at Time of 45 Years after Placement

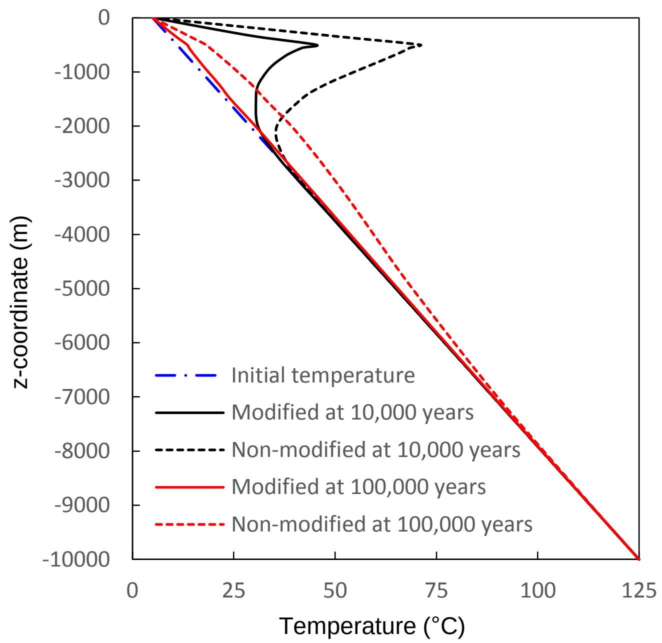


Figure 5-8: Comparison of Modified and Non-modified Temperature after 10,000 Years and 100,000 Years from Near-field Model with Initial Temperature

5.1.2.5 Thermal and Mechanical Influence of a Repository in Crystalline Host Rock on the Ground Surface

Guo (2016b) describes the thermal and mechanical influence of a single-level conceptual deep geological repository in a hypothetical crystalline host rock geosphere on the ground surface.

Sensitivity studies are performed to investigate the influence of Young's modulus for the rock, the depth of the repository and the convective heat transfer coefficient applied at the ground surface. The influence of the mechanical boundary condition applied on the far-field vertical surfaces is also studied.

For the cases evaluated, the presence of the conceptual DGR does not have any significant influence on the surface temperature. There is a general slow uplift of the ground surface due to thermal expansion over an area larger than the repository footprint, with a maximum uplift of about 28 cm occurring above the centre of the repository in about 3,400 years (Figure 5-9).

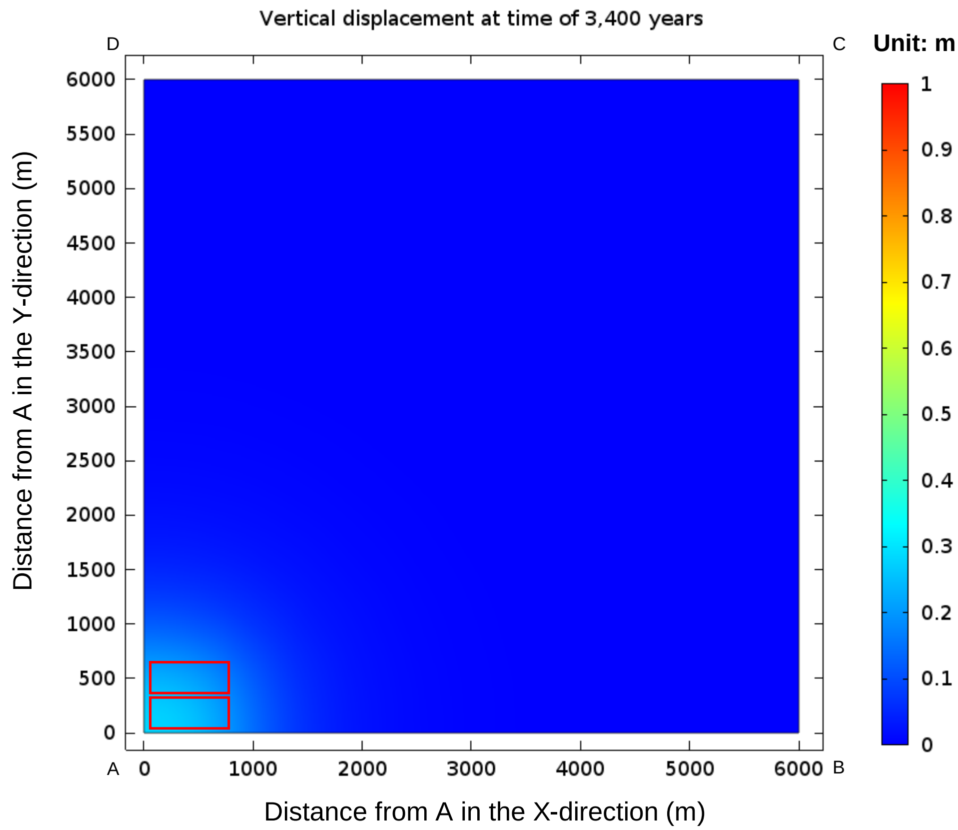


Figure 5-9: Vertical Displacement of the Ground Surface after 3,400 Years

The simulated maximum depth of rock experiencing tensile stress is 11 m for the case with all intact rock (Figure 5-10), and about 45 m for the case with a 150 m overlying layer of fractured rock (Figure 5-11).

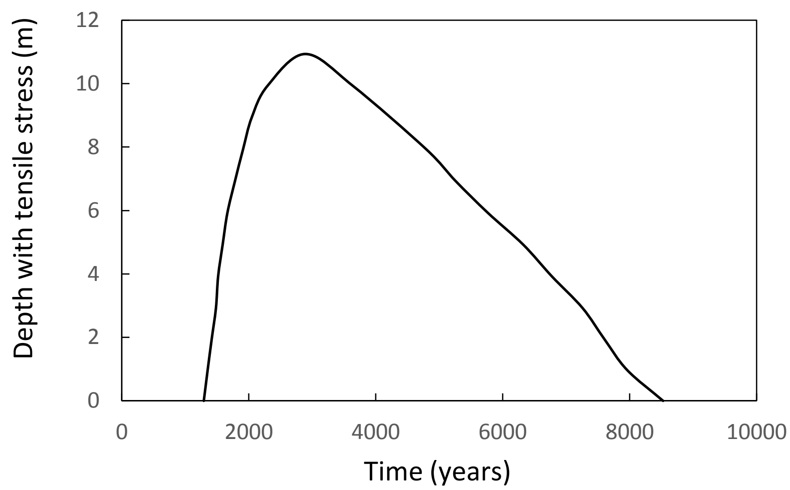


Figure 5-10: Tensile Stress Depth in Rock

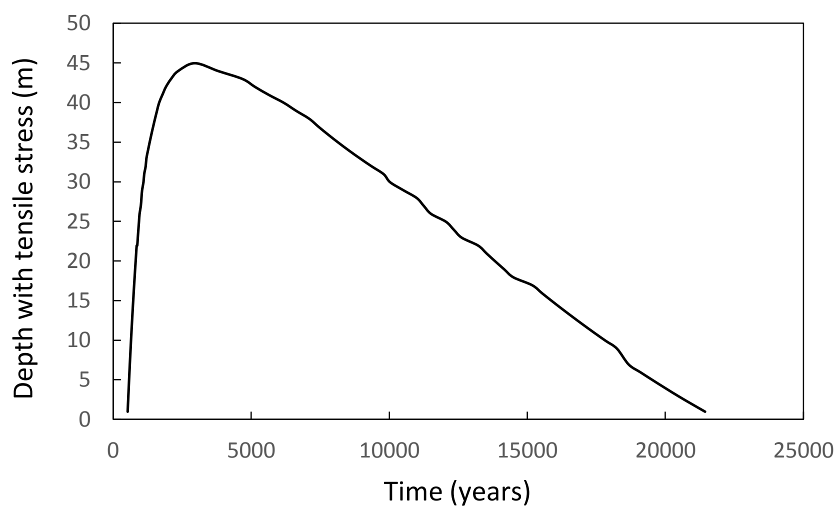


Figure 5-11: Tensile Stress Depth in Rock for the Case with the 150 m Top Layer of Rock Fractured

Simulations show that increasing the depth of the DGR does not cause any significant change in the thermal and mechanical influence on the ground surface.

5.1.2.6 Reactive Transport Modelling of Concrete-Bentonite Interactions

Reactive transport modelling is a useful tool to understand and predict the long-term performance of concrete-bentonite interface in the near-field of a DGR for spent nuclear fuel. The multi-component reactive transport code MIN3P-THCm (Mayer et al. 2002; Mayer and MacQuarrie 2010) has been developed at the University of British Columbia for reactive transport simulation of geochemical processes occurring in engineered barriers (bentonite) via the Äspö EBS TF-C benchmark work program (Xie et al. 2014). The code was also previously used to simulate the geochemical evolution at the interface between clay and concrete (Marty et al. 2015). In 2017, MIN3P-THCm will be used to perform reactive transport simulations in the near-field to investigate the long-term chemical evolution at the bentonite-concrete interface, hosted in either sedimentary or crystalline rock. These simulations will keep track of the temporal evolution of the mineralogical assemblage at the interfaces between bentonite and concrete, and concrete and the host rock. The simulations will also include a conceptual representation of porosity changes, associated changes in effective diffusion coefficients, and feedback onto the transport regime. Simulation results will be compared for scenarios with and without porosity feedback. In addition, the migration of radionuclides (e.g., iodine-129) through the altered bentonite-concrete-host rock system will be simulated in a conceptual manner for scenarios with constant and evolving porosity.

5.1.3 Biosphere Modelling

5.1.3.1 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 also is used in recent safety assessments for a conceptual repository in crystalline rock (NWMO 2012a) and sedimentary rock (NWMO 2013).

In Europe, the calculation of dose consequences to non-human biota is largely performed using the ERICA approach (e.g., Torudd 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 two radionuclide partitioning methods: the transfer factor approach and concentration ratio approach. The transfer factor approach estimates the concentration in mammals and birds based on the intake rate of food, soil, water or sediment, and the concentration ratio approach estimates the concentration in all organisms based on the concentration in the media (soil, water, sediment or air). 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 non-human biota dose assessment approach was completed in 2014 and revised in 2015 (Medri and Bird 2015). This non-human biota dose assessment approach was also used to complete an illustrative non-human biota dose assessment for a repository in both crystalline and sedimentary rock (Medri 2015a). In 2016, the approach was used to evaluate dose consequences to non-human biota for an updated illustrative safety assessment for a repository in crystalline rock.

5.1.3.2 Chemical Toxicity

Five major postclosure safety assessments have been completed that examine the long-term safety implications of a hypothetical deep geological repository for used fuel. These safety assessments focused on radiological consequences; however, because a repository contains a variety of other materials, some of which are chemically toxic in large enough quantities, analyses of non-radiological consequences have also been included in these safety assessments.

Criteria for evaluating the chemical toxicity of all chemical elements relevant to a used fuel repository were originally developed for the Atomic Energy of Canada Limited (AECL) Environmental Impact Statement case study. Since then, numerous updates have been completed. With the addition of a sediment medium and the differentiation between surface water and groundwater media, these criteria were updated for use in the subsequent postclosure safety assessments for hypothetical sites in crystalline (NWMO 2012a) and sedimentary (NWMO 2013) rock environments. The revised set of interim acceptance criteria were documented in a report issued in early 2015 (Medri 2015b). Criteria are referred to as "interim" because they have not been formally approved for use in a used fuel repository licence application. The report presents the comprehensive set of interim acceptance criteria for all relevant elements in a used fuel repository. It also documents the basis for the interim acceptance criteria for five environmental media: groundwater, surface water, soil, sediment and air.

A contract was established in 2016 to perform a literature review and develop interim non-radiological acceptance criteria for a subset of elements that are missing from NWMO's compilation (Medri 2015b).

5.1.3.3 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. These projects are typically co-sponsored by several national waste management organizations. In 2016, the NWMO sponsored the following projects.

<u>COMET Workshop on Effects of Radiation on the Environment</u>

A BIOPROTA representative attended an international workshop entitled: "Thirty years after the Chernobyl accident: what do we know about the effects of radiation on the environment?". The workshop was held in Chernihiv (Ukraine), not far from Chernobyl. It focused on past and current studies of the effects of radiation on the environment in the Chernobyl Exclusion Zone, as well as studies near Fukushima. Highlights included a discussion of the resolution of the anomalies between field and laboratory studies and the implication of the Chernobyl and Fukushima studies for current benchmark dose rates to non-human biota.

C-14 Project

C-14 is one of the key radionuclides of interest in post-closure assessments for solid radioactive waste disposal facilities. However, uncertainties remain with regard to the behaviour of C-14 in the environment and how these affect long-term dose assessments. The main purpose of this program is to further understanding of the behaviour of C-14 in the surface environment and to improve assessment approaches. In 2013, a refereed paper on this work was published in the Radiocarbon Journal (Limer et al. 2013). In 2014, a workshop on this topic was held in France and the workshop report was subsequently issued (BIOPROTA 2014). In 2016, another workshop was held in France to discuss model-data and model-model comparisons for three C-14 scenarios covering atmospheric deposition, release to sub-soil and modelling of contamination from an historical near-surface disposal. The project report is due to be completed in 2017.

BIOMASS Update

The International Atomic Energy Agency (IAEA) BIOMASS report on reference biospheres for solid radioactive waste disposal was published in 2003, following an extensive international collaborative work program running from 1996 until 2001. The methodology has been used to support a wide range of radioactive waste disposal assessments. BIOPROTA has undertaken to reviewing and enhancing the BIOMASS methodology in light of experience, new knowledge and developments since 2001. The work programme is being co-ordinated with IAEA MODARIA II working group 6 (WG6), which also aims to further develop and enhance the BIOMASS methodology, taking into account the output from the BIOPROTA project. To this end, BIOPROTA held two workshops in 2016 and published workshop reports identifying key areas of review and update of the BIOMASS methodology (Smith 2016, 2017).

Based on the discussions at these workshops, the current aim is to update the BIOMASS methodology to retain the same basic methodological steps (i.e., not to change the overall approach), but to bring it up-to-date based on new information, experience in application, revised international recommendations and regulatory practice. A report is expected to be published at the conclusion of the project in 2017.

Issues Affecting the Assessment of Impacts of Disposal of Radioactive and Hazardous Waste

Two workshops have been organised though BIOPROTA to consider the non-radiological post-disposal impacts of radioactive waste disposal. The first addressed the scientific basis for long-term radiological and hazardous waste disposal assessments. Building on the discussion from the first workshop, a second workshop was held focusing more precisely on comparison of safety and environmental impact assessments for disposal of radioactive waste and hazardous wastes.

The issues emerging from the second workshop were presented at the BIOPROTA Annual Meeting in 2015 and discussed further at the Continuing Issues Workshop held in the same week. They are summarised as follows:

1. Criteria for human and environmental health protection from the non-radiological hazards;
2. Limits on package content of hazardous chemicals in radioactive waste packages;
3. Application of groundwater protection legislation to radioactive waste repositories;

4. Feasibility of developing a single toxicity index that addresses the chemical and radiation hazards associated with solid waste on a consistent and equitable basis;
5. Consistent and coherent assessment of disposal of waste containing naturally occurring radioactive material (NORM) and other radioactive waste in the same disposal facility; and
6. Disposal of low-level and/or very low-level radioactive waste with other waste in facilities not specifically intended for radioactive waste.

The project aims to provide information that supports the development of a consensus on how to address these issues, leading to the application of more coherent and consistent assessment methods. A project report is expected in 2017.

5.1.4 System Modelling

The postclosure safety assessment of a used fuel repository uses several complementary computer models, as identified in Table **5.2**. These are either commercially maintained codes, or codes maintained by the NWMO software quality assurance program.

Table 5.2**: Main Safety Assessment Codes for Preclosure and Postclosure Analyses**

Software	Version	Description / Use
SYVAC3-CC4	4.09.2	Reference integrated system model
FRAC3DVS-OPG	1.3	Reference 3D groundwater flow and transport code
T2GGM	3.2	3D two-phase gas and water flow code
AMBER	6.1	Generic compartment modelling software
COMSOL	5.2a	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 section describes code-related activities conducted in 2016.

5.1.4.1 Updates to SYVAC3-CC4

Software updates to the integrated system model SYVAC3-CC4 (NWMO 2012b) in 2016 consisted of updates to correct minor errors in the code (e.g., output formatting for some parameters). Corrections were applied to the SYVAC3 executive controller portion of the SYVAC3-CC4 code and the CC4 system model portion remained unchanged.

The SYVAC3-CC4 validation efforts were most recently documented in Garisto and Gobien (2013). New tests completed in 2016 using the current version SYVAC3-CC4.09.2 include:

1. Comparison of the results from the geosphere network model (GEONET) for a larger number of elements and for an All Containers Fail Disruptive Scenario with FRAC3DVS-OPG v1.3; and,

2. Comparison of the container release model in CC4 for the Mark II container and repository design with COMSOL v5.2.

Overall, simulated near-field and geosphere transport in the SYVAC3-CC4 model was found to compare well with the more detailed COMSOL and FRAC3DVS models for a variety of radionuclides. Transport results for non-sorbing species were nearly identical and SYVAC3-CC4 results were conservative for highly sorbing species. Validation of the SYVAC3-CC4 code will continue as an on-going effort in 2017.

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 also are underway. The following sections describe work undertaken in both of these subject areas.

5.2.1 Preclosure Studies

5.2.1.1 Preliminary ALARA Dose Assessment

In 2014, a preliminary ALARA (As Low As Reasonably Achievable) dose assessment was carried out to guide development of the Mark I and II concepts and to provide the data to further optimize shielding and facility conceptual designs (Reijonen et al. 2014). The main findings were that workers involved in the receipt of Used Fuel Transport Packages (UFTP) have the highest normal dose exposure and that inclusion of a wall around the UFTP storage area would reduce worker dose considerably.

In 2016, the preliminary ALARA report was updated for the Mark II conceptual design, so that it would be consistent with the latest Used Fuel Packaging Plant and repository design. The 2016 update uses a more realistic estimate of the facility throughput, incorporates the main design change recommended by the 2014 assessment (i.e., storage wall around UFTP storage), and adheres to the radiation area zonings of the conceptual design. The assessment concludes that the total annual dose rate is projected to be modestly lower than the previous estimate due primarily to additional shielding in the UFTP area.

5.2.1.2 Preliminary Hazard Identification

Operational safety is an important aspect in the development of the deep geological repository concept. In 2014, a preliminary hazard identification study was initiated. Failure modes and effects analysis was used to review the process steps for UFPP operations above ground and repository operations below ground, and to identify potential hazardous events and accident scenarios that may have a radiological consequence during facility operation. The process steps were defined based on the preliminary ALARA study (Reijonen et al. 2014). Internal and external initiating events were considered and grouped based on anticipated initiating event frequencies:

- Anticipated Operational Occurrences (AOOs): events with annual frequencies > 10^{-2};
- Design Basis Accidents (DBAs): events with annual frequencies > 10^{-5} but < 10^{-2};
- Beyond Design Basis Accidents (BDBAs): events with annual frequencies < 10^{-5} but > 10^{-7}; and
- Non-Credible Scenarios: events with annual frequencies < 10^{-7}.

Initiating event frequencies are estimates only at this early design stage.

For the Mark II design, twenty-three AOOs, six DBAs and four BDBAs have been identified. In most cases, the consequence of these events is an extended outage period at the UFPP, with no releases. A Technical Report was issued to document the preliminary hazard identification study for the Mark II (Reijonen et al. 2016).

In 2017, preliminary radiological dose calculations will be carried out for potential public exposure under these identified accident scenarios.

5.2.1.3 The Repository Metadata Management Project

The Repository Metadata (RepMet) Management Project (NEA 2014) is aiming to create sets of metadata that can be used by national programmes to manage their repository data, information and records in a way that is harmonized internationally and suitable for long-term management. RepMet deals with the period before closure; however, the Project will have a strong connection to another NEA initiative, the Preservation of Records, Knowledge and Memory across Generations (see Section 5.2.2.4). In 2016, the NWMO provided funding to this program.

5.2.2 Postclosure Studies

5.2.2.1 Features, Events, and Processes

Features, Events and Processes (FEPs) refers to those factors that may need to be considered as part of a safety assessment. As part of each assessment, NWMO reviews each of these factors and provides a screening analysis indicating whether or not it should be included within the detailed safety assessment. This helps provide a completeness check on the assessment, i.e., that all relevant factors are being considered.

The FEPs assessment for the Sixth Case Study has been completed and is currently being reviewed. This assessment is, in many respects, similar to that for the Fourth Case Study (Garisto 2012). Major differences arise due to adoption of the smaller copper coated used fuel container for the Sixth Case Study and the repository design.

5.2.2.2 Glaciation in a Sedimentary Rock Environment

The NWMO completed a study illustrating the postclosure safety of a deep geological repository located in the sedimentary rock of the Michigan Basin in Southern Ontario (NWMO 2013). The study used three-dimensional groundwater flow and transport modelling to simulate the transport of radionuclides from a defective container. The Normal Evolution Scenario documented in the study assumed constant climate conditions and consequent steady-state flow for the 1 Ma performance period. The effects of expected glaciation and possible associated erosion were not explicitly modelled, but were instead assumed to be inconsequential based on results of regional-scale paleohydrogeologic simulations. Actual glaciation effects were acknowledged as a key uncertainty in the final Pre-Project Report.

In 2014, a study was initiated to explicitly evaluate possible effects of glaciation. An existing glacial climate realization was used as the basis for repeating glaciation conditions over the next 1 Ma (Peltier 2011). Sub-regional flow models for the sedimentary rock in southern Ontario were developed to examine the effects of glacial surface hydraulic heads, glacial hydro-mechanical loading, erosional unloading and permafrost on the flow system. Boundary conditions and loadings were extracted from sub-regional models and then applied to smaller-scale transient flow and radionuclide transport models incorporating the conceptual repository and engineered barrier systems. Cases were simulated for the Reference Case geosphere and several source-release and water-supply well locations. Sensitivity cases were conducted for geosphere properties, boundary conditions, two-phase flow, initial conditions, transport properties, and two variants of erosion processes. In all cases, the repository performance remained robust, with transport remaining diffusion-dominated due to very limited effects on the deep geosphere flow system. Results of this work have been documented in a Technical Report (Avis and Calder 2015).

5.2.2.3 Assessment of Repositories with the Mark II Engineered Barrier System

In 2016, the NWMO completed an assessment of the postclosure performance of a conceptual repository design for crystalline host rock that incorporates the Mark II EBS. The report will be published in 2017.

5.2.2.4 Preservation of Records, Knowledge and Memory across Generations

The NEA Radioactive Waste Management Committee initiative on the Preservation of Records, Knowledge and Memory across Generations (NEA 2015) was launched to minimise the risk of losing records, knowledge and memory, with a focus on the period of time after repository closure. In 2016, the NWMO provided funding to this program.

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APPENDIX A: TECHNICAL REPORTS, RESEARCH PAPERS AND CONTRACTORS

A.1 NWMO Technical Reports

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

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Keech, P.G. Canada's Plan for Nuclear Waste at National Ilan University Yilan City, Taiwan (R.O.C.), October 8, 2015.

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Keech, P.G. Long-Term Management of Canada's Used Nuclear Fuel, guest lecture in Radioactive Waste Management – Design at University of Ontario Institute of Technology, Oshawa, ON. 2011-2015, annually.

Keech, P.G., P. Jakupi, S. Ramamurthy, J. Chen, R. Jacklin, R. Partovi-Nia and D. Shoesmith. Copper Coatings for Used Nuclear Fuel Containers: Corrosion Testing, International Society of Electrochemistry 2015 Annual meeting, Taipei, Taiwan, October, 2015.

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A.3 LIST OF RESEARCH COMPANIES, SPECIALISTS AND UNIVERSITIES

Aalto University
Amec Foster Wheeler
ANCAM Solutions Company Ltd
Atomic Energy of Canada Limited
Canadian Hazards Information Services
CanmetMATERIALS
Commissariat à l’énergie atomique et aux énergies alternatives
EcoMetrix Inc.
ETH-Zurich
GB Environmental Consulting
Geofirma Engineering Ltd
Geological Survey of Canada
Golder Associates Ltd
Integran Technologies Inc.
Integrated Technologies Inc
Integrity Corrosion Consulting Ltd.
Itasca Consulting Group Inc.
McGill University
McMaster University
Mirarco
NAGRA
National Research Council Canada - Industrial Materials Institute (Boucherville, Quebec)
Natural Resources Canada
Novika Solutions
Paul Scherrar Institute
Penn State University
Posiva
Queen’s University
Royal Military College of Canada
Ryerson University
SENES Consultants Limited
SKB International Consultants
United States Geological Survey
University of Bern
University of British Columbia
University of New Brunswick
University of Ottawa
University of Saskatchewan
University of Toronto
University of Waterloo
University of Windsor
University of Western Ontario
University of Virginia
Western University
York University

APPENDIX B: ABSTRACTS FOR TECHNICAL REPORTS FOR 2016

ABSTRACT

Title: **Technical Program for the Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2015**
Report No.: **NWMO-TR-2016-01**
Author(s): R. Crowe, K. Birch, J. Freire-Canosa, J. Chen, D. Doyle, F. Garisto, P. Gierszewski, M. Gobien, C. Hatton, N. Hunt, S. Hirschorn, M. Hobbs, M. Jensen, P. Keech, L. Kennell-Morrison, E. Kremer, J. McKelvie, C. Medri, M. Mielcarek, A. Murchison, A. Parmenter, R. Ross, E. Sykes, T. Yang
Company: Nuclear Waste Management Organization
Date: April 2016

Abstract
This report is a summary of activities and progress in 2015 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 its used nuclear fuel. Significant technical program achievements in 2015 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's research program published 20 NWMO technical reports, submitted 19 papers for journal publication and 46 abstracts for presentation at national and international conferences focused on environmental radioactivity and radioactive waste management.

- 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, case studies and methods for detailed site investigations in both crystalline and sedimentary rock in the fields of: geology, hydrogeochemistry, isotope geochemistry, paleohydrogeology, sub-surface mass transport, geomechanics, seismicity, geochronology, microbiology and long-term climate change. NWMO continued to develop and sponsor modelling and analytical methods that will be used to assess long-term geosphere barrier integrity.

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

ABSTRACT

Title: **Preliminary Hazard Identification for the Mark II Conceptual Design**
Report No.: **NWMO-TR-2016-02**
Author(s): Heini Reijonen [1], Taina Karvonen [1] and José Luis Cormenzana [2]
Company: [1] Saanio & Riekkola Oy
[2] Empresarios Agrupados Internacional, S.A.
Date: January 2016

Abstract
Operational safety is an important aspect of concept development. This report describes the methodology used and results obtained from a preliminary hazard identification assessment performed for Adaptive Phased Management (APM)'s Mark II conceptual design. Failure Modes and Effects Analysis has been used to identify potentially hazardous events and accident scenarios that could result in an increase in radiological consequence during the operating period. Internal and external initiating events were considered.

The identified failure modes were grouped into the following categories based on the anticipated initiating event frequencies:

- Anticipated Operational Occurrences (AOOs): Events with frequencies > 10^{-2} a^{-1};
- Design Basis Accidents (DBAs): Events with frequencies > 10^{-5} a^{-1} but < 10^{-2} a^{-1};
- Beyond Design Basis Accidents (BDBAs): Events with frequencies < 10^{-5} a^{-1} but > 10^{-7} a^{-1}; and
- Non-credible Events: Event with frequencies < 10^{-7} a^{-1}.

The estimation of initiating event frequencies is preliminary at this early design stage.

Based on this preliminary work, twenty-three AOOs, six DBAs, and four BDBAs have been identified, with most of these events resulting in extended outage periods at the Used Fuel Packaging Plant. Due to the high frequency of operations, the dropping of a module by the overhead transfer crane/gantry and the potential damage of fuel bundles during fuel transfer operations are identified in the AOO category.

The DBA category includes the failure and fall of an elevator during a used fuel transport package (UFTP) operation, the failure of the scissor lift resulting in the fall of a module/fuel bundles, a UFTP transport vehicle fire, a used fuel container (UFC) placement vehicle fire, the dropping of a UFTP containing an undetected flaw, and the dropping of an UFC containing an undetected flaw.

Shaft cage fall with an UFC, flooding of the repository facility, a major earthquake leading to repository cave-in, and repository collapse on the UFCs are all placed in the BDBA category.

The presence or absence of ventilation system filters is also considered in combination with specific accident scenarios.

ABSTRACT

Title: **Thermal Response of a Mark II Conceptual Deep Geological Repository in Crystalline Rock**
Report No.: **NWMO-TR-2016-03**
Author(s): Ruiping Guo
Company: Nuclear Waste Management Organization
Date: March 2016

Abstract
This report describes the thermal performance of a conceptual deep geological repository (DGR) involving the Mark II container and placement concept in a hypothetical crystalline rock environment.

A series of design studies for conceptual DGRs has been carried out over the past 30 years. These studies include two- and three-dimensional thermal transient and thermo-mechanical analyses. For numerical reasons, they are divided into far-field modelling and near-field modelling. In the Near-Field Models, an adiabatic thermal condition is applied on the four vertical outside boundaries, and as such, this represents a repository with an infinite horizontal dimension. The results from such models are known to be accurate at early times, with the thermal response overestimated at longer times.

To examine the influence of this boundary condition, thermal near-field modelling is performed for the Mark II repository using COMSOL and a method is proposed to account for boundary condition influences. The method is validated by comparing the modified COMSOL results with a theoretical solution produced using HOTROK.

A great portion of the temperature change at later times in the non-modified near-field modelling results is attributed to the effect of the adiabatic condition applied on the four vertical boundaries. The modified analysis shows that the thermal peak occurs early in the life of the repository and there is no comparable second peak after thousands of years for the case described in this report.

For the case evaluated, the maximum container surface temperature is 84°C occurring after 45 years, the maximum temperature of the room centre between two containers is 83°C occurring after 45 years, and the maximum temperature of the rock is 77°C occurring at the room roof above the top layer container after 65 years.

ABSTRACT

Title: **Dolomitization: Cambrian and Ordovician Formations in the Huron Domain**
Report No.: **NWMO-TR-2016-05**
Author(s): Ihsan Al-Aasm
Company: University of Windsor
Date: January 2016

Abstract
A preliminary study has been completed to examine the paleogenesis of strata-bound dolomite found occurring in deep-seated Ordovician and Cambrian sediments on the eastern flank of the Michigan Basin. As part of the study seven samples were analyzed for petrographic, stable and Sr isotopic composition, and fluid inclusion microthermometry to characterise dolomitization. The samples represented a range of host rocks from dolomitized limestones, dolostones, sandy dolostones and sandstones within Ordovician Black River Group and underlying Cambrian formation. The petrographic and geochemical attributes have provided a basis to gain insight on the source fluids that modified these rocks, as well as, the possible timing of formation.

Evidence indicates that the formations were subject to higher temperatures than can be explained by burial history alone. This suggests the occurrence and migration of hydrothermal fluids within the low permeability dolomite horizons, possibly during Paleozoic orogenesis. Calcite fracture infill isotopic and fluid inclusion data point to two possibly isolated diagenetic fluid systems; i) an earlier Cambrian system that is characterized by a more radiogenic, cooler and saline signature; and ii) a later Ordovician system that is characterized by hypersaline, more hydrothermal and a less radiogenic fluid system. The observation of highly discrete, strata-bound dolomites combined with only trace quantities of saddle dolomite and its associated geochemical signature suggest that diagenesis, as a result of hydrothermal fluids, was neither pervasive in volume or extent at the Bruce nuclear site.

ABSTRACT

Title: **Continued Application of U-Pb Geochronology Methods to the Absolute Age Determination of Secondary Calcite: 2014-2016**
Report No.: **NWMO-TR-2016-07**
Author(s): Donald W. Davis
Company: University of Toronto
Date: July 2016

Abstract

Previous results reported by Davis (2013) determined that uranium-lead geochronology techniques, including laser ablation inductively-coupled mass spectrometry and thermal ionization mass spectrometry, were suitable for assessing the timing of emplacement of secondary vein and vug calcite in deep Ordovician and shallow Devonian-aged carbonate sedimentary rocks of the Michigan Basin. The current report presents results on the absolute age determination of 15 additional secondary calcite samples. These samples were collected from drill core of Devonian and Silurian age from the Paleozoic carbonate sedimentary rocks beneath the Bruce nuclear site, near Tiverton, Ontario (Intera, 2011; NWMO, 2011). The current report also includes revised previous results from Davis (2013) that together summarize the current understanding of the geochronology of secondary calcite mineral emplacement within the Paleozoic bedrock on the eastern flank of the Michigan Basin beneath the Bruce nuclear site.

The new data presented herein reveal a complex history of fluid mobility, and vein and vug emplacement ranging from late during the Paleozoic Era to the Pleistocene. Samples that extend down to approximately 180 metres vertical depth below ground surface (Upper Silurian Bass Islands Formation) show evidence for multiple secondary calcite ages ranging between ca. 100 and 0 Ma. Secondary calcite from the deeper Silurian Salina A1-Unit yields an age of 318 ± 10 Ma, as well as, scattered younger ages.

Some of the LA-ICPMS data acquisition methods employed by Davis (2013) were identified for additional refinement, including the selection of the most suitable analytical standard and the selection of optimal laser beam wavelength for data collection. In addition, new software has been employed for processing the LA-ICPMS data. The outcome is a statistically more robust methodology for the application of U-Pb geochronology techniques to secondary calcite.

ABSTRACT

Title: **Determination of Sorption Properties for Sedimentary Rocks Under Saline, Reducing Conditions – Key Radionuclides**
Report No.: **NWMO-TR-2016-08**
Author(s): F. Paul Bertetti
Company: Center for Nuclear Waste Regulatory Analyses, Southwest Research Institute
Date: June 2016

Abstract
This report summarizes the results of an experimental project designed to measure sorption values for the key redox-sensitive radioelements uranium (U), selenium (Se), arsenic (As), technetium (Tc), neptunium (Np), and plutonium (Pu). The experiments investigated sorption of the elements on three substrates—two Canadian sedimentary rock types (exemplified by samples of Queenston Shale and Cobourg Limestone) and a bentonite—and were conducted in synthetic brine solutions (SR-270-PW) and dilute solutions under low-O_2, reducing conditions.

Protocols were developed to (i) ensure repeatable generation of brine solutions meeting target compositions; (ii) ensure accurate pH and Eh measurements in the brines; and (iii) establish an appropriate reducing environment for the experiments. Kinetics and batch sorption tests were conducted.

Results of the sorption experiments indicated that the highest distribution coefficients (K_ds) in brine and dilute solutions were associated with Pu and U. Sorption of Se and As was moderate in the brine and dilute solutions. Tc and Np showed variable sorption behaviour. In a long-running batch test, Tc showed strong sorption to limestone and MX-80, but low sorption on shale. Measured Np sorption was low in brine solutions but strong (equivalent to that of U) in dilute solutions. Experimental solution conditions were confirmed to be significantly reducing and targeted Eh values were met in most cases. Where Eh values were higher than desired, the experimental results did not indicate changes in behaviour of the elements being tested.

For some elements such as Np, Pu, and U, multiple experiments demonstrated consistent sorption results over various conditions. Sorption in brines was lower for Np, Pu, and U than in dilute solutions. Sorption in brine and dilute solutions was similar for As, Se, and Tc. There was typically no significant difference in measured sorption for the different substrates examined in these tests. With the exception of Np, it is likely that the experiments adequately evaluated the targeted valence state for the radioelements tested [As(III), Pu(III/IV), Se(−II), Tc(IV), and U(IV)]. Although not confirmed by direct measurement, support for these valence states includes preparation of stock solutions in the expected form (As), preparation based on previously known techniques to generate reduced valence state (Pu, Se, and U), comparative evidence for sorption of oxidized and reduced forms (Tc, U, and Pu), and comparisons of the results to sorption values presented in the literature.

The results of the sorption experiments will be used to update the NWMO's database of sorption values for Canadian sedimentary rocks and bentonite for use in the evaluation of potential deep geological repository (DGR) sites.

ABSTRACT

Title: **Nuclear Fuel Waste Projections in Canada – 2016 Update**
Report No.: **NWMO-TR-2016-09**
Author(s): M. Garamszeghy
Company: Nuclear Waste Management Organization
Date: December 2016

Abstract
This report summarizes the existing inventory of used nuclear fuel wastes in Canada as of June 30, 2016 and forecasts the potential future arisings from the existing reactor fleet as well as from proposed new-build reactors. While the report focuses on power reactors, it also includes prototype, demonstration and research reactor fuel wastes held by AECL which are included in the NWMO mandate.

As of June 30, 2016, a total of approximately 2.7 million used CANDU fuel bundles (approx. 54,000 tonnes of heavy metal (t-HM)) were in storage at the reactor sites, an increase of approximately 82,000 bundles from the 2015 NWMO Nuclear Fuel Waste Projections 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 3.5 to 5.4 million used CANDU fuel bundles (approx. 70,000 t-HM to 108,000 t-HM), depending upon future decisions to life-extend the 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 additional refurbishment beyond what has already been completed), while the upper end assumes that most reactors are refurbished and life extended for an additional 25 EFPY of operation. The upper end has increased from the 2015 report, due to the announced plans to refurbish and life-extend the Darlington and Bruce reactors.

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 formal licensing has already been initiated are eventually constructed (i.e. at Darlington, which was granted a site preparation licence by the Canadian Nuclear Safety Commission in 2012), 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 2015 report. Assuming 4 new CANDUs, the total number of CANDU fuel bundles could be 7.0 million.

When reactors refurbishments are completed and/or decisions on future reactor refurbishment, new nuclear build or advanced fuel cycle technologies 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: **Sixth Case Study: Reference Data and Codes**
Report No.: **NWMO-TR-2016-10**
Author(s): M. Gobien, F. Garisto, E. Kremer and C. Medri
Company: Nuclear Waste Management Organization
Date: December 2016

Abstract
The Sixth Case Study is an illustrative postclosure safety assessment of a conceptual repository for used nuclear fuel located at 500 m depth at a hypothetical site on the Canadian Shield.

The conceptual design differs from the previous case studies in that it considers horizontal in room placement of smaller (48 bundle) used fuel containers. The reference used fuel container design has also been updated: it retains the outer copper for corrosion protection and inner steel vessel for structural support; however, the copper is now electroplated or cold-sprayed directly onto the outer steel vessel, rather than being a separate shell. This copper coating is much thinner than the copper shell.

The hypothetical site where the repository is excavated is the same as in the Fourth Case Study (NWMO 2012a); however, a different realization of the fracture system is used. In this study, the exact repository location has shifted approximately 3500m to the north west, the room spacing has decreased from 40 m to 20 m and the repository remains at 500 m Below Ground Surface (mBGS).

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

- FRAC3DVS-OPG – for 3D groundwater flow and radionuclide transport;
- RSM – a simple screening model used to identify the key radionuclides;
- SYVAC3-CC4 – the primary safety assessment system model (container, repository, geosphere, biosphere);
- HIM – for calculating dose consequences for the inadvertent human intrusion scenario.

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

The reference datasets are based on a combination of the site conceptual model information and the repository design description, with most of the general material properties and other input parameters adopted from previous work. Updated data were used when available from more recent studies. This report provides a summary of all the data selected, and indicates the references where more details about the derivation of the data may be found.

ABSTRACT

Title: **Review of the NWMO Copper Corrosion Program**
Report No.: **NWMO-TR-2016-11**
Authors: John R. Scully[1], Damien Féron[2], Hannu Hänninen[3]
Company: [1]University of Virgina, USA
[2]CEA, France
[3]Aalto University, Finland
Date: August 2016

Abstract

Beginning in 2011, the Nuclear Waste Management Organization (NWMO) initiated a design change for their deep geological repository (DGR) system for the long-term storage of used nuclear fuel. In addition to significant changes to emplacement and clay buffer methods, a primary change was the adoption of a copper-coated used fuel container (UFC). To support this vessel, the NWMO initiated a series of copper corrosion related research programs, to compliment the many years of research that have been previously performed on copper for its use in DGRs. As much of this historic work has been previously reviewed [Scully & Edwards 2013], an emphasis within this current review was placed on the active copper corrosion programs, and the potential impacts of copper corrosion mechanisms to the copper-coated UFC. The review panel concluded that the NWMO has developed a well-integrated and world-leading research team to conduct this work, through a combination of academic institutions, industrial consultants and international collaborations. The research effort is extensive, and can be summarized in the following statements:

- The programs have been well designed to address the specific requirements of copper-coated UFCs in anticipation of the eventual licensing such a container. Future efforts and funding should remain within the existing topics: anoxic corrosion of copper; radiolysis related corrosion of copper; copper coating vs. wrought copper corrosion; localized corrosion of copper. Possible enhancements of research as proposed by the review team will fall into these categories.

- In addition to supporting the use of copper coatings, the programs are providing significant data for the generic use of copper as a DGR material within an eventual license application. On-going partnerships with other international organizations responsible for nuclear waste management have produced a mutually beneficial knowledge database that will continue to build confidence in this topic.

- The NWMO has developed a clear path forward with respect to continued research on copper corrosion as its proceeds to a site selection and the site-specific chemistry that will be produced in the future. The successful conclusion of the existing corrosion programs combined with the future programs that incorporate site-specific data are highly likely to support very long lifetime predictions for UFCs (i.e., 100,000 y), provided supporting assumptions with respect to geochemistry, environment, bentonite clay performance, as well as container/bentonite manufacturing can be substantiated.

Information from parallel research in microbial processes affecting DGRs was also provided, but was not the scope of this review. Nonetheless, it was clear that the NWMO microbial and corrosion programs are well integrated, and supportive of each other.

The review also focused on uncertainties within the prediction of copper corrosion, and a series of recommendations with respect to future work were derived. Using the same topic breakdowns as above, these are:

- Anoxic copper corrosion investigations should emphasize efforts for identifying the source and technical basis for hydrogen observed during experiments in pure water and brine. In addition, the effect of sulphide as a catalyst for anoxic corrosion should be specifically assessed;

- Radiolysis copper corrosion programs require an additional effort to integrate the experimental results that are providing enhanced understanding of mechanisms, etc., into applied results, such as rate laws or understanding of processes that contribute towards understanding the basis for estimating a corrosion allowance;

- Copper coating investigations should focus on ensuring a continuing characterization of samples that use the actual selected manufacturing processes, and the resultant corrosion behaviour as the NWMO develops a final manufacturing method. The technical basis for any differences in corrosion behavior between electrodeposited copper and wrought copper should be understood; this includes sulphide induced corrosion, radiolytic corrosion, and anoxic modes (i.e., any that contribute to the corrosion allowance calculation);

- Localized corrosion research should continue to define differences between active and passive conditions to ensure that corrosion via pitting does not occur. Long-term testing is encouraged.

An additional recommendation from this review is that:

- The internal corrosion program should include specific investigations with respect to the evolved hydrogen, and its eventual fate (i.e., sources and sinks) inside a used fuel container.

With respect to the related microbial programs not evaluated in this review, the NWMO is encouraged to conduct a future peer review, with the specific goals of assessing these programs, as well as their integration with the corrosion programs.

ABSTRACT

Title: **The Greenland Analogue Project: Final Report**
Report No.: **NWMO-TR-2016-12**
Authors: Claesson Liljedahl L[1], Kontula A[2], Harper J[3], Näslund J-O[1], Selroos J-O[1], Pitkänen P[2], Puigdomenech I[1], Hobbs M[4], Follin S[5], Hirschorn S[4], Jansson P[6], Kennell L[4], Marcos N[7], Ruskeeniemi T[8], Tullborg E-L[9], Vidstrand P[1]
Company: [1]Svensk Kärnbränslehantering AB, [2]Posiva Oy, [3]University of Montana, [4]NuclearWaste Management Organization (NWMO), [5]Golder associates, [6]Department of Physical Geography, Stockholm University, [7]Saanio & Riekkola Oy, [8]Geological Survey of Finland, [9]Terralogica AB
Date: September 2016

Abstract
This report summarises the key findings of the Greenland Analogue Project (GAP), a collaborative research project conducted between 2008 and 2013 by the national nuclear waste management organisations in Sweden (SKB), Finland (Posiva) and Canada (NWMO). The primary aims of the GAP were to enhance scientific understanding of glacial processes and their influence on both surface and subsurface environments relevant to the performance of deep geological repositories for spent nuclear fuel in crystalline shield rock settings. Based on its size, relative accessibility, and crystalline shield bedrock, the Greenland Ice Sheet (GrIS) was selected by the GAP as a natural analogue for glaciation processes expected to reoccur in Fennoscandia and Canada over *Deep Geological Repository* (DGR) safety-relevant timeframes.

The GAP study area is located east of Kangerlussuaq village on the west coast of Greenland and covers approximately 12,000 km2, of which approximately 70% is occupied by the GrIS. To advance understanding of glacial hydrogeological processes, GAP research activities included both extensive field work and modelling studies of the GrIS, focused into three main project areas: 1) surface-based ice sheet studies; 2) ice drilling and direct studies of basal conditions; and 3) geosphere studies. The main objectives and activities of these project areas are provided below:

1. Surface-based ice sheet studies aimed to improve the current understanding of ice sheet hydrology and its relationship to subglacial hydrology and groundwater dynamics. This work was based primarily on *indirect* observations from the ice sheet surface of the basal hydrological system, to obtain information on parts of the ice sheet which contribute water for groundwater infiltration. Project activities included quantification of ice sheet surface water production, as well as an evaluation of how water is routed from the ice surface to the interface between the ice and the underlying bedrock.

2. Ice drilling and direct studies of basal conditions also aimed to improve understanding of ice sheet hydrology and groundwater formation based on *direct* observations of the basal hydrological system, paired with numerical ice sheet modelling. Specific processes were investigated, including: 1) thermal conditions within and at the base of the ice sheet; 2) generation of meltwater at the ice/bedrock interface; and 3) hydrologic conditions at the base of the ice sheet. Activities included ice drilling of multiple holes at three locations on the ice sheet, at distances up to thirty kilometres from the ice sheet terminus, to assess drainage, water flow, basal conditions and water pressures at the interface between the ice and bedrock.

3. Geosphere investigations focused on groundwater flow dynamics and the chemical and isotopic composition of water at depths of 500 metres or greater below ground surface, including evidence on the depth of permafrost, redox conditions and the infiltration of glacial meltwater into the bedrock. Deep and inclined boreholes were drilled through the permafrost in the vicinity of the ice sheet margin. The boreholes were hydraulically tested and instrumented to allow hydrogeologic and hydrogeochemical monitoring. The nature of ground conditions under a proglacial lake was also investigated, to assess if areas of unfrozen ground within the permafrost (taliks) may act as a potential pathway for exchange of deep groundwater and surface water.

The key findings from these three main project areas contribute towards improved scientific understanding of processes associated with the GrIS. Several highlights are summarised below, in terms of attributes relevant to assessing the long term safety of a DGR.

Transient meltwater processes on the ice sheet surface: Surface melt and runoff is a summer phenomenon limited to 3-4 months (May through September), during which time the ice surface lowers by up to 3-4 metres. The volume of meltwater generated at the surface each summer exceeds the amount of predicted basal melt by two order of magnitude (cm of basal melt vs. metres of surface melt). The summer melt period therefore completely dominates the annual cycle of available water volume. Abrupt draining of supraglacial lakes (SGLs) into newly opened fractures is one of the key mechanisms for establishing surface-to-bed pathways. Nearly all surface melt eventually penetrates the ice and reaches the bed. Just above the *equilibrium line altitude* (ELA), where meltwater begins to pool, is approximately the interior limit where substantial surface melt has the potential to penetrate to the bed. Seasonal variations in water flow through the basal drainage system beneath the ablation zone occur mainly as the result of ice sheet surface melting.

Basal thermal distribution and generation of water at the ice sheet bed: Direct observations made in 23 boreholes drilled to the ice sheet bed at distances between 200 m and 30 km from the ice margin provide the first direct evidence that the entire outer flank of the study area has a melted bed, with liquid water present, rather than a universally or locally frozen bed. No evidence has been found to suggest that a complex pattern of patchy frozen/melted bed conditions exist in the ice marginal areas within the region studied. Modelling results illustrate that the location of the boundary between melted and interior frozen conditions is highly sensitive to geothermal heat flux values, but relatively insensitive to longitudinal ‘pulling’ caused by fast sliding ice flow near the margin. For all choices of boundary conditions and modelling parameters believed to be reasonable, a central frozen area extends many tens of kilometres from Greenland’s central ice flow divide, but greater than 75% of the studied sector of the GrIS is subject to basal melting conditions.

Hydraulic boundary conditions for groundwater simulations: Hydrologic conditions at the ice sheet bed were found to vary across the width of the GAP study area. Between the ice divide and the margin, there is evidence for three different basal zones as defined by the amount and configuration of meltwater: the *frozen bed zone*, the *wet bed zone*, and the *surface-drainage bed zone*. The *surface-drainage bed zone* is further characterised by a zone with *distributed water drainage* and a zone with *transient conduit drainage*. These hydrological zones result from surface, bed, and internal ice flow processes, and may be representative of Northern Hemisphere ice sheets in a similar stage of development to the current GrIS. This revised conceptual understanding of the drainage system developed through the GAP implies that much of the bed inward of the margin is covered by water, rather than mostly drained by discrete conduits with little water in between. Further, the drainage system would not be expected to undergo large pressure drops in response to water input forcing, as hypothesised for a conduit dominated system that rapidly drains high volumes of water from the bed. Taken together, hydraulic measurements and analyses from the ice boreholes imply that ice overburden hydraulic pressure (i.e. a hydraulic head corresponding to 92% of ice thickness) provides an appropriate description of the basal hydraulic pressure as an average value for the entire ice sheet over the year.

Role of permafrost and taliks: The GAP study area is located in a region with continuous permafrost. Close to the ice sheet margin, the permafrost thickness reaches 350-400 m, as measured in the DHGAP03 and DH-GAP04 boreholes. The main part of the base of the ice sheet in the study area, including marginal areas, has been shown to have basal melting conditions, with the exception of the central parts of the ice sheet. Taken together with the fact that most of the area presently glaciated was also glaciated throughout the past 10,000 years (and therefore, has not been subject to any sub-aerial permafrost development during this time), indicates that permafrost does not exist under the major part of the large, warm-based areas of the ice. An exception is at the ice margin, where a wedge of permafrost most likely stretches in under the ice. It is not known how far this subglacial permafrost wedge stretches (e.g. if it is a few hundreds of metres or several kilometres).

Where permafrost extends to depths of greater than 300 m, a lake diameter of approximately 400 m would be expected to maintain unfrozen areas throughout the entire permafrost thickness, e.g. through taliks, which provide a potential pathway for exchange of deep groundwater and surface water. Borehole DH-GAP01 was drilled underneath a lake (“Talik lake”), confirming for the first time, the existence of a through talik beneath a lake in an area of continuous permafrost. Furthermore, sampling of this borehole has provided the first information on groundwaters from within a talik located in close proximity to the ice sheet margin. Although it has been hypothesised that the Talik lake would act entirely as a discharge feature, evidence from hydraulic head measurements and the stable water isotopic composition of the sampled groundwaters are consistent with seasonal recharging conditions occurring at this location.

Meltwater end-member water compositions: The characteristics of a meltwater end-member are needed when evaluating water compositions in glaciated areas, as well as in any numerical modelling of groundwater flow and reactive solute transport. Based on analysis of meltwater compositions conducted as part of the GAP and reported in the scientific literature, a glacial meltwater end-member has depleted δ18O (-30 to -25‰) and δ2H signatures (-235 to -200‰) consistent with cold climate conditions and a very low total dissolved solids content, with solute concentrations ranging from practically zero to approximately 1 mM for the main solutes, such as Ca2+.

Depth of glacial recharge: The stable water isotopic signatures (δ2H and δ18O) indicate that the groundwater sampled in both boreholes (DH-GAP01, DH-GAP04) are of glacial meltwater origin. The millions of years of predominantly glacial conditions in this region, the local structural geology and fracture distribution, the presence of high hydraulic gradients and the presence of relatively low salinity fluids at depth in the rock mass have likely facilitated the penetration of glacial meltwaters at this site to depths of a least 500 m.

The relatively low concentrations of Na and Cl in the groundwaters likely originate from within the rock matrix through water-rock interactions and diffusion, whereas Ca and SO4 in these waters originate from dissolution of gypsum, with occurs as a fracture infill mineral at depths below approximately 300 m. A preliminary interpretation of dissolved He concentrations suggests that the deep groundwaters may have residence times exceeding hundreds of thousands of years. Together with the extensive persistence of gypsum (hydrothermal origin) below 300 m, which is a highly soluble mineral, this suggests stable conditions with limited groundwater flow at depths below 300 m at the DH-GAP04 location.

Redox stability of the groundwater system: Below the permafrost (and/or at depths greater than about 350 m), reducing conditions are interpreted to prevail in the study area. Past penetration into the bedrock of dissolved oxygen in meltwaters has been limited in depth, as indicated by the presence of pyrite in 8 fractures below approximately 50 m; iron oxyhydroxides are found in fractures only in the upper parts of the rock (down to 60 m), with only a few isolated occurrences of goethite down to 260 m depth.

The above examples illustrate ways in which research conducted within the GAP has advanced scientific understanding of hydrological processes related to the presence of an ice sheet, including the temporal and spatial nature of processes occurring on the ice sheet surface, conditions at the ice sheet bed (thermal and meltwater generation), and interactions between glacial meltwater and the underlying groundwater systems. In assessments of the potential risk to humans and the environment from DGRs for spent nuclear fuel, uncertainties related to process understanding are typically handled using assumptions which over- rather than underestimate the potential radiological consequences. The increased scientific understanding of glacial hydrological processes attained through the GAP, and the associated reduction of uncertainties, has provided new insights that will inform and strengthen future safety cases, including the safety assessments developed for DGRs in crystalline bedrock settings. Furthermore, the findings may allow a re-evaluation of the degree of pessimism in some of the assumptions made in previous safety assessments and modelling work.

ABSTRACT

Title: **The Greenland Analogue Project: Data and Processes**
Report No.: **NWMO-TR-2016-13**
Author(s): Harper J[1], Hubbard A[2], Ruskeeniemi T[3], Claesson Liljedahl L[4], Kontula A[5], Hobbs M[6], Brown J[1], Dirkson A[1], Dow C[7], Doyle S[2], Drake H[8], Engström J[3], Fitzpatrick A[2], Follin S[9], Frape S[10], Graly J[11], Hansson K[12], Harrington J[11], Henkemans E[10], Hirschorn S[6], Humphrey N[11], Jansson P[13], Johnson J[1], Jones G[7], Kinnbom P[14], Kennell L[6], Klint K E[15], Liimatainen J[5], Lindbäck K[13], Meierbachtol T[1], Pere T[5], Pettersson R[13], Tullborg E-L[16], van As D[15]
Company: [1]University of Montana, [2]Aberystwyth University, [3]Geological Survey of Finland, [4]Svensk Kärnbränslehantering AB, [5]Posiva Oy, [6]Nuclear Waste Management Organization, [7]Swansea University, [8]Linnæus University, [9]Golder associates, [10]University of Waterloo, [11]University of Wyoming, [12]Geosigma AB [13]University of Stockholm, [14]PKM Innovation AB, [15]Geological Survey of Denmark and Greenland, [16]Terralogica

Date: September 2016

Abstract

This report presents the methods, collected datasets, and the interpretations completed for the Greenland Analogue Project (GAP), a collaborative research project conducted between 2008 and 2013 by the national nuclear waste management organisations in Sweden (SKB), Finland (Posiva) and Canada (NWMO). The primary aims of the GAP were to enhance scientific understanding of glacial processes and their influence on both surface and subsurface environments relevant to deep geological repository (DGR) performance in crystalline shield rock settings. Based on its size, relative accessibility, and crystalline shield bedrock, the Greenland Ice Sheet (GrIS) was selected by the GAP as a natural analogue for glaciation processes expected to reoccur in Fennoscandia and Canada over DGR safety-relevant timeframes.

The GAP study area is located east of Kangerlussuaq village on the west coast of Greenland and covers approximately 12,000km2, of which approximately 70% is occupied by the GrIS. To advance understanding of glacial hydrogeological processes, GAP research activities included both extensive field work and modelling studies of the GrIS, focused into three main subprojects:SPA) surface-based ice sheet studies; SPB) ice drilling and direct studies of basal conditions; and SPC) geosphere studies. The main objectives and activities of these subproject areas are provided below:

SPA) Surface-based ice sheet studies aimed to improve the current understanding of ice sheet hydrology and its relationship to subglacial hydrology and groundwater dynamics. This work was based primarily on *indirect* observations fromthe ice sheet surface of the basal hydrological system, to obtain information on the parts of the ice sheet which contribute water for groundwater infiltration. Project activities included quantification of ice sheet surface-water production, as well as an evaluation of how water is routed fromthe ice surface to the interface between the ice and the underlying bedrock. Methods employed include: remote sensing, automatic weather station network, GPSmeasurements of icemotion, ground-penetrating radar and seismics.

SPB) Ice drilling and direct studies of basal conditions also aimed to improve understanding of ice sheet hydrology and groundwater formation based on *direct* observations of the basal hydrological system, paired with numerical ice sheet modelling. Specific processes were

investigated, including: 1) thermal conditions within and at the base of the ice sheet; 2) generation of meltwater at the ice/bedrock interface; and 3) hydrologic conditions at the base of the ice sheet. Activities included ice drilling of multiple holes at three locations on the ice sheet, at distances up to thirty kilometers fromthe ice sheet terminus, to assess drainage, water flow, basal conditions and water pressures at the interface between the ice and bedrock.

SPC) Geosphere investigations focused on groundwater flow dynamics and the chemical and isotopic composition of water at depths of 500 metres or greater below ground surface, including evidence on the depth of permafrost, redox conditions and the infiltration of glacial meltwater into the bedrock. Deep and inclined bedrock boreholes were drilled through the permafrost in the vicinity of the ice sheet margin. The boreholes were hydraulically tested and instrumented to allow hydrogeologic and hydrogeochemical monitoring. The nature of ground conditions under a proglacial lake was also investigated, to assess if areas of unfrozen ground within the permafrost (taliks) may act as a potential pathway for exchange of deep groundwater and surface water. A wide range of methods were applied by SPC to study the above including: geological, geophysical and surface water investigations, as well as bedrock borehole investigations.

ABSTRACT

Title: **Thermal and Mechanical Influence of a Deep Geological Repository in Crystalline Rock on the Ground Surface**
Report No.: **NWMO-TR-2016-15**
Author(s): Ruiping Guo
Company: Nuclear Waste Management Organization
Date: October 2016

Abstract
This report describes the thermal and mechanical influence of a single level conceptual deep geological repository (DGR) in a hypothetical crystalline host rock geosphere on the ground surface.

Sensitivity studies are performed to investigate the influence of Young's modulus for the rock, the depth of the repository and the convective heat transfer coefficient applied at the ground surface. The influence of the mechanical boundary condition applied on the far-field vertical surfaces is also studied.

For the cases evaluated, the presence of the conceptual DGR does not have any significant influence on the surface temperature. There is a general slow uplift of the ground surface due to thermal expansion over an area larger than the repository footprint, with a maximum uplift of about 28 cm occurring above the centre of the repository in about 3,400 years.

ABSTRACT

Title: **Improvements in Methodologies for Radiographic Measurement of Diffusion Properties in Low-permeability Rocks, and Development of Methods for pH Measurement in Brines**
Report No.: **NWMO-TR-2016-16**
Author(s): Yan Xiang, Diana Loomer, Tom Al
Company: University of New Brunswick
Date: June 2016

Abstract
The objectives of this research are to develop and improve methodologies for measurement of diffusion properties in low-permeability sedimentary and crystalline rocks, and to develop methods for measurement of pH in high-ionic-strength aqueous solutions. Four separate projects are described.

The first project involved improvement and further development of the radiography method by using a monochromatic Am-241 γ-ray source. The use of monochromatic γ-radiation (γ-RAD) eliminates beam hardening which is a limitation to the precision and accuracy of the X-ray radiography technique. With the elimination of beam hardening, the γ-RAD technique allows for reliable calibration that is essentially independent of background matrix.

In the second project, diffusion coefficients for iodide (I^-) tracer were measured simultaneously using γ-RAD and through-diffusion on granite. Although only one test was conducted, the results indicate that the γ-RAD method will be a viable alternative to through-diffusion for measurements on very-low-porosity crystalline rocks.

The third project focused on the investigation of the effect of partial gas saturation on diffusion coefficients. A method has been developed to generate partial gas saturation in a rock sample by equilibrating the porewater with nitrogen (N_2) gas at high pressure (up to 7000 kPa) and then rapidly lowering the N_2 pressure to atmospheric. The degree of partial saturation is determined by the γ-RAD method. The effective diffusion coefficient (D_e) for iodide tracer at 100% brine saturation was compared to that at different degrees of partial gas saturation. A preliminary result from Queenston Formation shale indicates a 53% decrease in D_e as a result of 14.6% partial gas saturation. The results indicate good potential for evaluating the effect of partial saturation on diffusion in the low-permeability rocks that contain high salinity porewater.

The fourth project focussed on pH measurement in high-ionic-strength brine solutions. Buffers of varying composition and ionic strength were formulated and their pH values were determined by geochemical modelling using the Pitzer ion-interaction approach implemented in the geochemical program PHREEQC. These buffers were used to investigate two methods for pH measurement: potentiometric measurements with glass electrodes, and spectrophotometric measurements using the colorimetric indicator phenol red.

The pH electrode response is linear over a range from 1.4 to 9.1 and for ionic strengths up to 8.2 mol/kg. However, there is a systematic offset with increasing ionic strength such that an electrode calibrated with low-ionic-strength buffers will underestimate pH of a high-ionic-strength solution (8.2 mol/kg) by 0.6 to 0.7 pH units. For any given ionic strength, the potentiometric measurement is also sensitive to the ionic composition of the solution. Despite these effects, accurate potentiometric measurements are possible if the composition of the

calibration buffers is similar to the test solution. The results of spectrophotometric measurements indicate that the disassociation constant (pK'_a) of the phenol red indicator is virtually insensitive to the ionic composition of the solution. A maximum error of 0.2 units is possible for pH measured spectrophotometrically if the ionic strength of the buffers does not match the ionic strength of the test solution. However, the measurement range of phenol red is limited to a pH range from ~7 to 9; additional indicators can be used to increase the effective range for the spectrophotometric approach.

ABSTRACT

Title: **Sensitivity Analyses of Surface Boundary Conditions During Long-Term Climate Change**
Report No.: **NWMO-TR-2016-19**
Author(s): Gordan Stuhne and W. Richard Peltier
Company: University of Toronto, Department of Physics
Date: October 2016

Abstract
A set of 107 numerical simulations of the evolution of surface boundary conditions over a 122.5 kyr glacial cycle is analyzed in order to estimate the sensitivity of predictions to variations in key parameters of the University of Toronto Glacial Systems Model (UofTGSM). As described in a previous Report (TR-2015-16) that introduced reference surface boundary condition datasets deriving from a typical parameter regime (i.e., from the SeaRISE protocols for modern Greenland and Antarctic climate change studies), individual simulations are globally constrained by a data assimilation procedure that nudges simulated North American ice thickness histories towards the observationally well-validated ICE-6G_C reconstruction. The incorporation of nudging distinguishes sensitivity to ice model parameters from sensitivity to paleoclimate conditions that are very poorly constrained over the portion of the glacial cycle preceding Last Glacial Maximum (LGM). In earlier sensitivity analyses that referred to a smaller number of simulations deriving from a previous version of the UofTGSM (the GSM model of Tarasov and Peltier, 1999, 2002, 2003, 2004), Peltier (2006, 2011) showeddifferences between realizations to be dominated by pre-LGM paleoclimate-dependent fluctuations that were inconsistent with the eustatic sea-level record. Beyond considering a larger number of realizations deriving from a state-of-the-art version of the UofTGSM, the new sensitivity analyses described herein focus upon the bounds in surface boundary conditions associated with specific structures (e.g., glacial margins and ice domes) within the possible, observationally consistent ICE-6G_C ice thickness reconstruction. The parameter-sensitivities of ice thickness, permafrost thickness, basal temperature, meltwater production, lake depth, basal velocity, and basal shear stress are of the same order of magnitude as the amplitudes of predictions in Peltier (2006, 2011) and TR-2015-16 across a variety of simulation ensembles and nudging time scales.

ABSTRACT

Title: **Seismic Activity in the Northern Ontario Portion of the Canadian Shield Annual Progress Report for the Period January 01 – December 31, 2015**
Report No.: **NWMO-TR-2016-21**
Author(s): J. Adams[1], V. Peci[2], S. Halchuk[1] and P. Street[1]
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Date: December 2016

Abstract
The Canadian Hazards Information Service (CHIS), a part of the Geological Survey of Canada (GSC), continues to conduct a seismic monitoring program in the northern Ontario and eastern Manitoba portions of the Canadian Shield. This program has been on-going since 1982 and is currently supported by a number of organizations, including the NWMO. A key objective of the monitoring program is to observe and document earthquake activity in the Ontario portion of the Canadian Shield. This report summarizes earthquake activity for the year 2015.

CHIS maintains a network of sixteen seismograph stations to monitor low levels of background seismicity in the northern Ontario and eastern Manitoba portions of the Canadian Shield. Core stations are located at: Sioux Lookout (SOLO), Thunder Bay (TBO), Geraldton (GTO), Kapuskasing (KAPO), Eldee (EEO), and Chalk River (CRLO). These are augmented by the CHIS network of temporary stations at: Sutton Inlier (SILO), McAlpine Lake (MALO), Kirkland Lake (KILO), Sudbury (SUNO), Atikokan (ATKO), Experimental Lake (EPLO), Pickle Lake (PKLO), and Pukaskwa National Park (PNPO). The digital data from a temporary station at Victor Mine (VIMO), supported by the diamond mine industry, and a station at Pinawa (ULM), which has funding from the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO), are also used in this study.

All the stations are operated by CHIS and transmit digital data in real-time via satellite to a central acquisition hub in Ottawa. CHIS-staff in Ottawa integrate the data from these stations with those of the Canadian National Seismograph Network and provide monthly reports of the seismic activity in northern Ontario.

During 2015, 51 earthquakes were located. Their magnitude ranged from 1.2 m_N to 3.3 m_N. The largest event, with a magnitude of 3.3 m_N, occurred in the Temiscaming area, while the second largest event 3.1 m_N, occurred in Sudbury. The 51 events located in 2015 compares with the average of 60 per year from the prior 4 years.