Technical Program for Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2015

NWMO-TR-2016-01 **April 2016**

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Nuclear Waste Management Organization

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ABSTRACT

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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
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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.

TABLE OF CONTENTS

Page

LIST OF TABLES

Page

LIST OF FIGURES

Page

1. INTRODUCTION

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

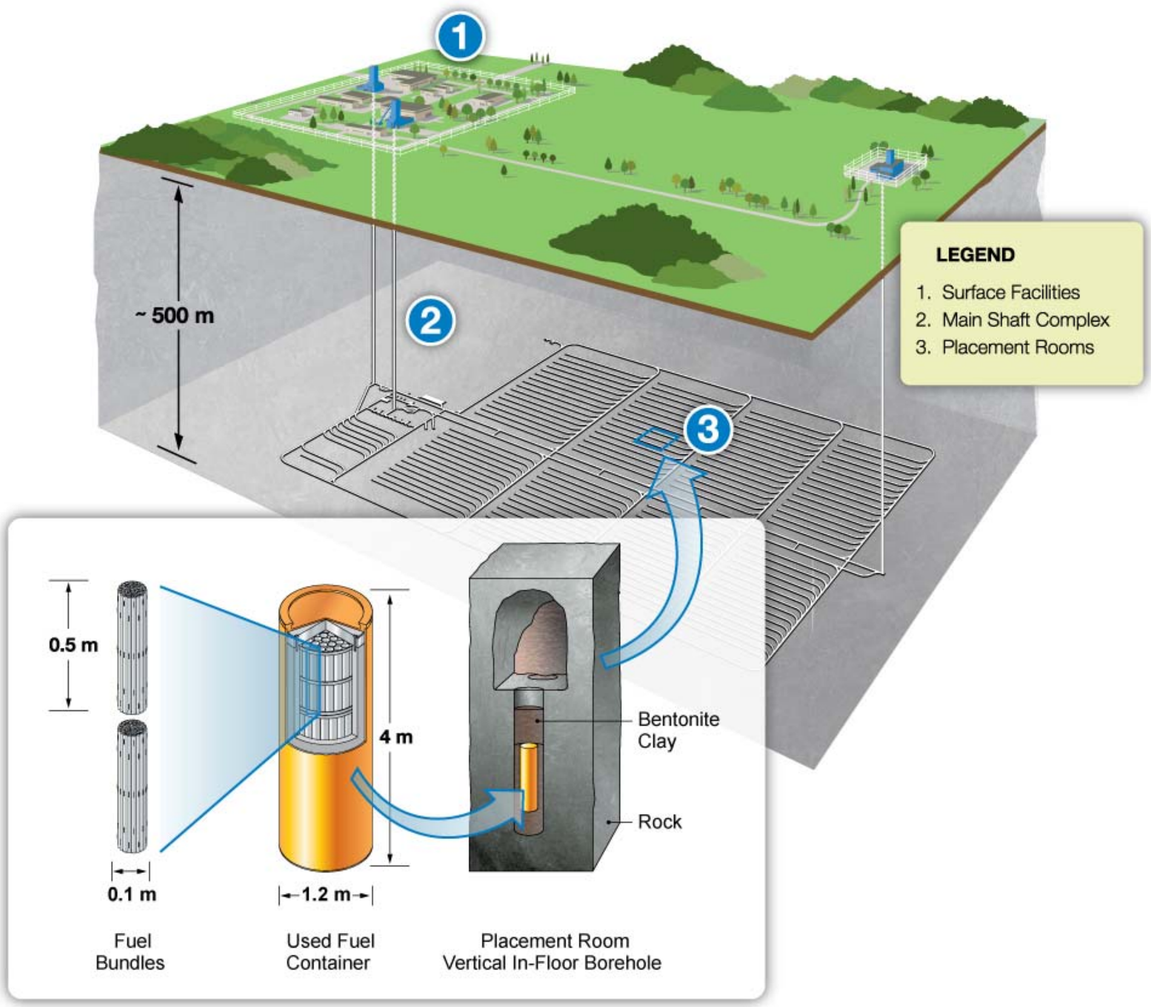


Figure 1.1: Illustration of a Deep Geological Repository – In-floor Borehole Placement (Mark I Design)

Work conducted and progress made within the APM Technical Program during 2015 is summarized in the remainder of this report. A brief update on the status of NWMO's site selection process is provided below.

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

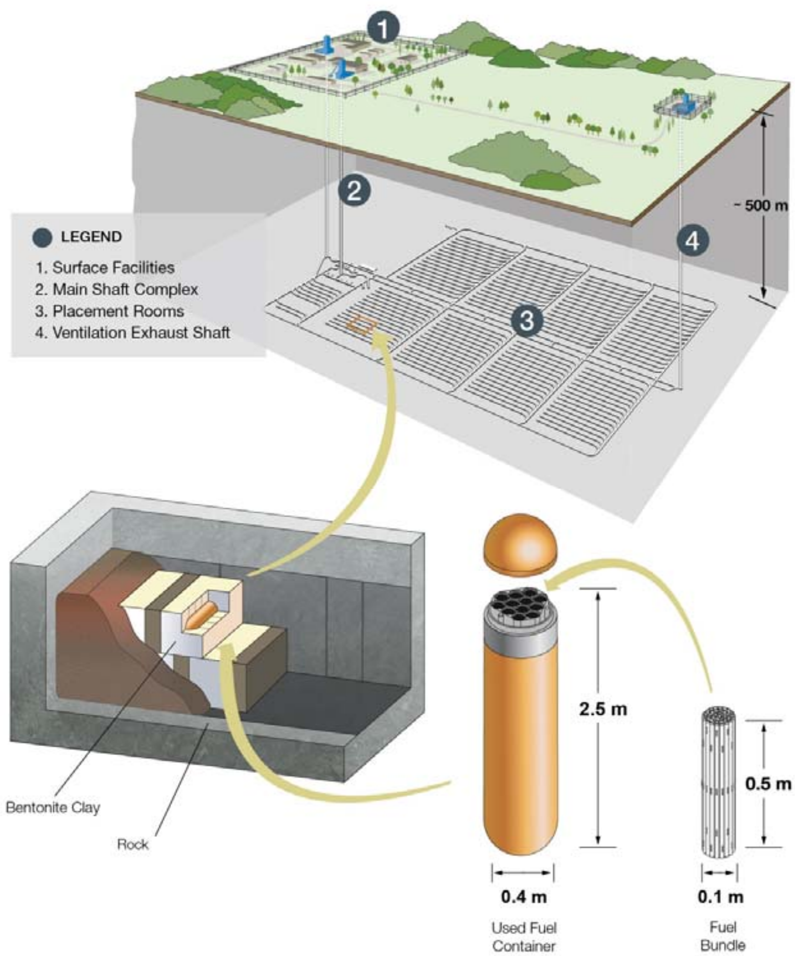


Figure 1.2: Illustration of a Deep Geological Repository – Horizontal Placement (Mark II Design)

NWMO completed initial screenings for ten communities in 2012 and moved on to feasibility studies in preparation for completing all initial screenings by 2014. The initial screening reports are published on NWMO's site selection website (http://www.nwmo.ca/sitingprocess).

For 2015, NWMO began with 13 communities still involved in various stages of learning about the plan and considering their interest in hosting the project. By year's end, 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 2015 is shown in Figure 1.3.

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

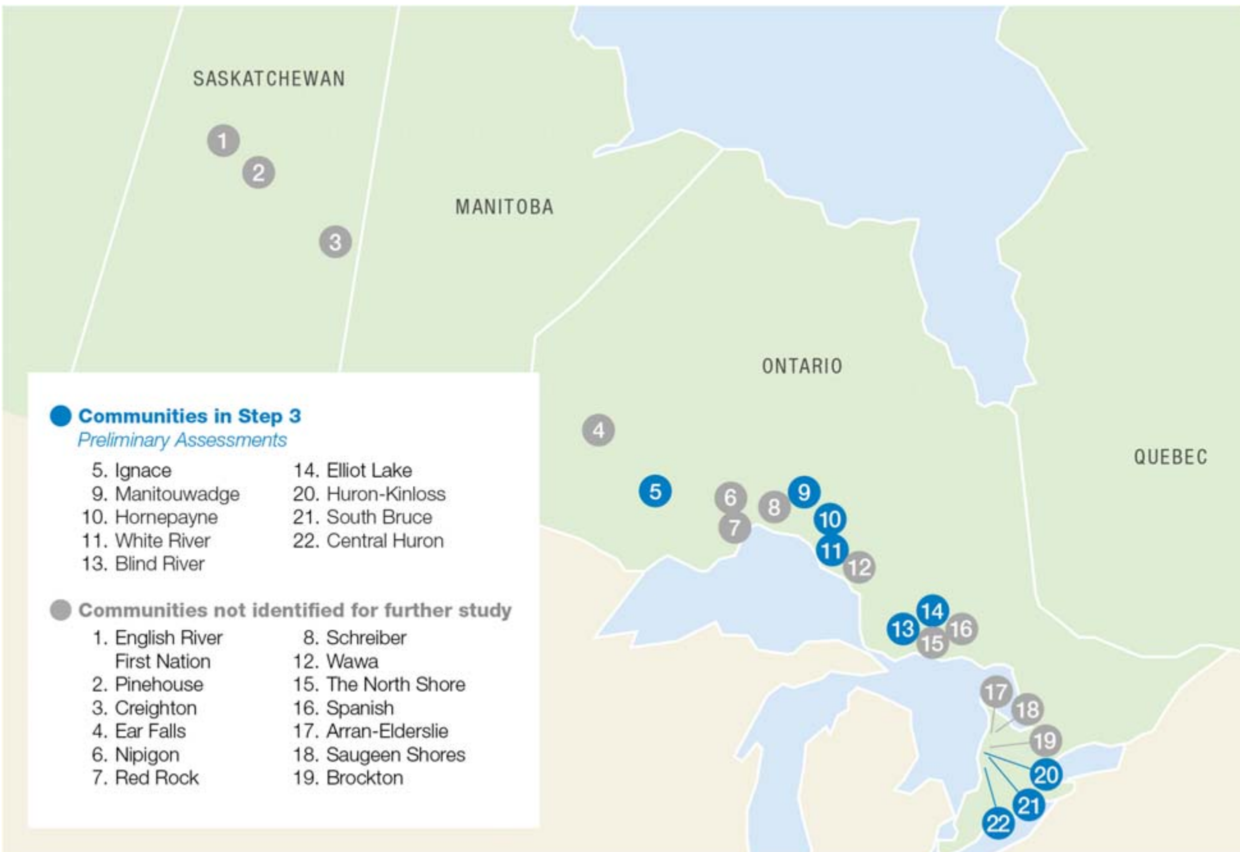


Figure 1.3: Communities Expressing Interest in the APM Siting Process and Current Status (December 31, 2015)

2. OVERVIEW OF CANADIAN RESEARCH AND DEVELOPMENT PROGRAM

2.1 REGULATORY FRAMEWORK

Implementation of a deep geological repository under Adaptive Phased Management falls within federal jurisdiction and will be regulated under the *Nuclear Safety and Control Act* (NSCA) and its associated regulations. The Canadian Nuclear Safety Commission (CNSC), as Canada's independent regulatory authority, regulates the use of nuclear energy and materials to protect the health, safety and security of Canadians and the environment, and implements Canada's international commitments on the peaceful use of nuclear energy. The CNSC also disseminates objective scientific, technical and regulatory information to the public.

Under section 26 of the NSCA, activities associated with a nuclear facility can occur only in accordance with a licence issued by the CNSC. The APM repository will be subject to the CNSC's comprehensive licensing system, which covers the entire life cycle of the repository, from site preparation to construction, operation, decommissioning (closure and post-closure) and abandonment (release from CNSC licensing). This stepwise approach will require a licence for each phase of the repository life cycle. The process for obtaining a "site preparation" licence is initiated by the NWMO. The NWMO would submit an application for a Licence to Prepare Site (and possibly construct) to the CNSC. A licensing decision by the CNSC on a repository can be taken only after the successful completion of the environmental assessment process, following the process established by the *Canadian Environmental Assessment Act*, 2012.

At this early stage, the NWMO has not submitted a licence application. Although no licence application has yet been made, as Canada's independent nuclear regulator, the CNSC adopts the best practice of getting involved early in proposed new nuclear projects to ensure that the future licence applicant and affected communities have a comprehensive understanding of the CNSC's role in regulating Canada's nuclear sector.

In recognition of the CNSC's early involvement, the NWMO signed an arrangement with the CNSC. In March 2014, it was renewed. As part of the arrangement, the CNSC is providing regulatory guidance to the NWMO and conducting pre-licensing reviews of conceptual designs and illustrative safety assessments in crystalline and sedimentary rock.

2.2 APM TECHNICAL PROGRAM OBJECTIVES & OVERVIEW

The primary objective of the APM Technical Program is to complete the preliminary designs, safety cases, cost estimates and research activities for a used fuel deep geological repository in order to support a licence application following planned selection of a preferred site in a 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 2015 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). 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.

2.3 SUMMARY OF INTERNATIONAL ACTIVITIES

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

- Since 2004, NWMO has been participating in experiments associated with the SKB Äspö Hard Rock Laboratory (HRL) in Sweden. The purpose of this participation is to improve our understanding of key processes in a repository in crystalline rock through involvement in large-scale projects. NWMO's involvement facilitates collaboration and the sharing of lessons learned in repository technology development and site characterization. In 2015, 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 NWMO has also been a partner in the Mont Terri Project, which consists of a series of experiments carried out in the Mont Terri Underground Research Laboratory (URL) in Switzerland. The experiments being conducted at Mont Terri are relevant to NWMO site characterization, engineering and safety assessment for sedimentary rock formations. Involvement in the Mont Terri Project allows NWMO to participate in state-of-science research in collaboration with 14 international project partners, including several waste management agencies. During the current phase of the Mont Terri Project, NWMO continues to be involved in the following experiments:

- Disturbances, Diffusion, Perturbation and Retention (DR-A) (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);
- Porewater Characterization (DB-A); and
- Full Scale Emplacement Experiment (FE-G, FE-M).

To advance the understanding of the impact of glacial processes on the long-term performance of a DGR, the Greenland Analogue Project (GAP), a four-year field and modelling study of a land-terminating portion of the Greenland ice sheet (2009-2012), located near Kangerlussuaq (Russell Glacier), was established collaboratively by 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 scientific understanding of glacial hydrological processes attained through the GAP will be documented in the two volume set of Greenland Analogue Project final reports to be published concurrently during 2016 (Claesson Liljedahl et al. *in press*; Harper et al. *in preparation*). In addition, 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. 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 then.

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

- Working Group on the Characterization, the Understanding and the Performance of Argillaceous Rocks as Repository Host Formations (i.e., Clay Club) Annual Meeting;

- Integration Group for the Safety Case (IGSC) Annual Meeting;
- Safety Case Symposium;
- Thermodynamic/Sorption Database Development Project;
- IGSC FEP Database Project;
- Radioactive Waste Management Committee (RWMC);
- RWMC Reversibility & Retrievability Project; and
- Preservation of Records, Knowledge and Memory Project.

NWMO continued its participation in BIOPROTA, the international working group on biosphere modelling. In 2015, 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 2015. 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 RECOVERY AND TRANSPORT

3.1.1 Design of the Basket Transportation Package

A conceptual design was produced for a transportation package for moving used nuclear fuel located at Point Lepreau and Gentilly-2 nuclear generating station sites. This package was needed because the used fuel is stored in cylindrical baskets rather than rectangular modules used at Ontario Power Generation sites. This new package has thus been named the Basket Transportation Package or BTP. The conceptual design process, supported by research into existing designs and basic thermal and shielding analyses, led to three distinct options which were evaluated and ranked using a decision matrix process. The conclusions of the conceptual evaluation are that the BTP design should proceed with the following features:

The package should:

- Be specifically designed to handle AECL-style used fuel baskets,
- Be cylindrical in shape,
- Incorporate a bolted closure,
- Use a groove or step in the body for tie-down/lifting, and
- Have a minimum wall thickness of 230.5mm (bounding – to be revised)

The BTP conceptual design will be evaluated in 2016 using advanced structural, thermal, and shielding analyses. These analyses will allow the designers to confirm the structural and thermal integrity, optimize geometry, and finalize key design features.

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

In order to demonstrate the robustness of the UFTP, NWMO designed and fabricated a mobile exhibit trailer featuring the UFTP-1. The trailer was commissioned in April 2013. In 2015 NWMO performed an annual safety inspection of the trailer as required by the Ontario Ministry of Transportation, performed annual maintenance as prescribed in the operator’s manual and conducted the annual visual inspection of the UFTP. During the 2015 summer season, the exhibit trailer appeared in 15 events spanning 26 days, attracting more than 1,500 visitors. The trailer travelled over 17,000 km to meet the schedule. A full size Dry Storage Container with lid and two used fuel modules were placed on display in the education and storage area of the NWMO Engineering Facility in Oakville, Ontario.

3.1.3 Public and Worker Dose Assessment

An assessment report estimating potential radiological dose which could be received by members of the public and transportation workers due to the transportation of used nuclear fuel by road using the Used Fuel Transportation Package (UFTP) was concluded in 2015. This dose assessment was based on real-world exposure time, distance and frequency data collected by a team of researchers from Carleton University, Ottawa. The Carleton researchers examined activities along a representative road route between the Darlington Nuclear Generating Station and the Township of Ignace, Ontario.

Using the Carleton data, doses to members of the public and transportation workers were calculated. The scenarios included residents along the transport route, individuals in vehicles sharing the transport route, individuals at rest stops, cyclists, used fuel transport drivers, transportation inspectors, roadside workers, etc. The calculated doses were compared to the regulatory dose limits defined in the Canadian Nuclear Safety Commission's Radiation (CNSC) Protection Regulations.

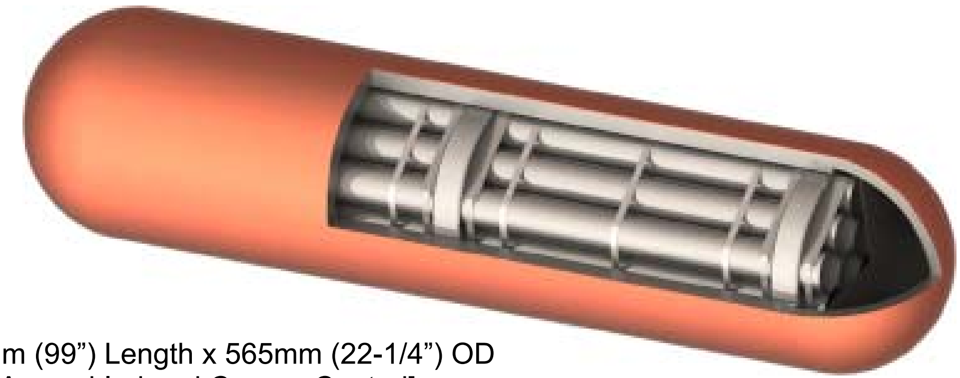
Doses to individuals ranged from 1.3×10^{-6} mSv per year for a hitchhiker along the transport route to 0.35 mSv per year for the driver. All doses were calculated to be below the regulatory dose limit of 1 mSv per year for a member of the public, therefore no individuals including transport workers like the driver are required to be designated as Nuclear Energy Workers (NEWs) under CNSC regulations.

3.2 USED FUEL CONTAINER (UFC)

In 2015, Repository Engineering continued the development and testing of the 48 bundle capacity Mark 2 Used Fuel Container (shown in Figure 3.1: and Figure 3.1:). This effort is part of the multi-year Proof Test Program to validate the design of the UFC steel core and copper coating external corrosion barrier. Significant in 2015 was the first full-scale external pressure test applied to a prototype Mark 2 container. This experimental test result was an important milestone in the NWMO UFC design engineering program as it confirmed the ability of the numerical Finite Element Analysis (FEA) model to predict UFC performance under glacial loading conditions.

In addition to manufacturing development and structural testing programs, a continuation of fundamental corrosion research was carried out for both copper (external corrosion barrier) and steel (the structural component) to acquire additional data to predict material performance under DGR conditions.

The results of these programs are reported in the following sections.



2515mm (99”) Length x 565mm (22-1/4”) OD
[Assembled and Copper Coated]

Figure 3.1: Illustration of NWMO’s Mark 2 Used Fuel Container Consisting of Steel Containment (core), External Copper Coating and Internal Fuel Baskets

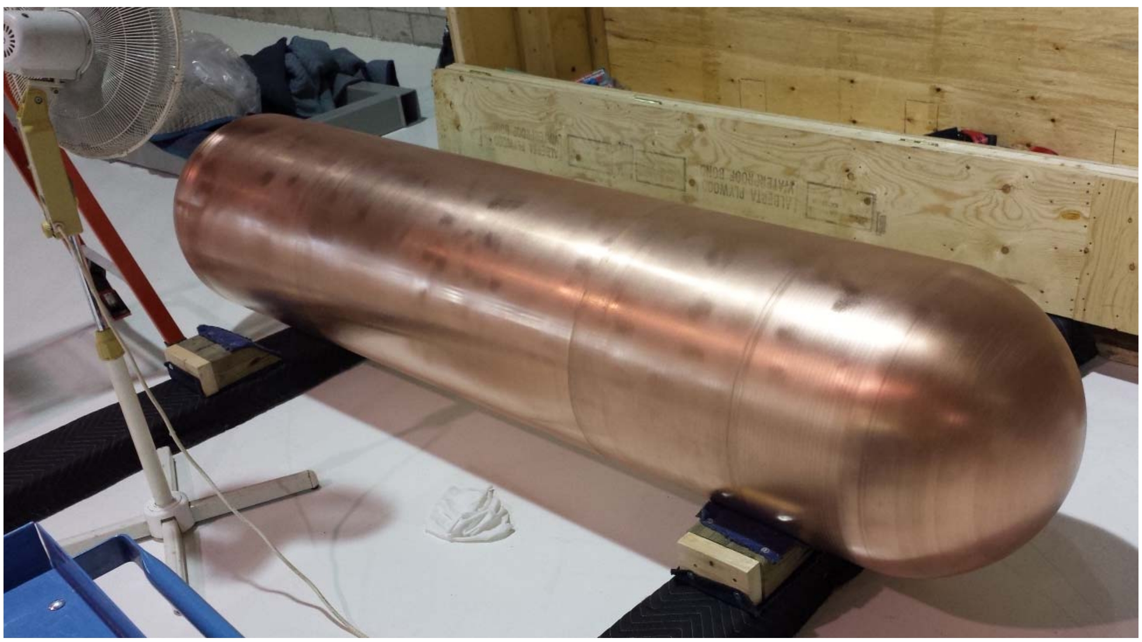


Figure 3.2: Leading Copper Coated Mark 2 Used Fuel Container

3.2.1 Used Fuel Container Manufacturing & Inspection Development

In the past year NWMO continued the demonstration of Hybrid-Laser-Arc-Welding (HLAW) for use in the assembly of the UFC steel core via the application of a partial penetration weld. Concurrent with the HLAW program is the UFC Machining Program whereby input on HLAW weld joint dimensional requirements, component fit-up and tolerances are being established for the fabrication of prototypes. In addition, a comprehensive Non-Destructive Examination program was launched for the development of inspection techniques for the examination of the UFC closure weld and copper coating. These programs are being integrated with the fabrication of six UFC prototypes which is currently underway.

3.2.1.1 HLAW Closure Welding Development

NMWO's welding vendor (Novika Solutions) performed a comprehensive HLAW process optimization study in 2015 to determine weld parameter tolerance boxes within which sound closure welds can be consistently made under a specified range of weld joint fit-up conditions. Following this study, Novika prepared a Welding Procedure Specification (WPS) and Procedure Qualification Record (PQR) in accordance with ASME Sections IX and III (Division 3 Subsection WC) to qualify the optimized reference parameters. Figure 3.3: shows the test assembly fabricated for PQR testing from which coupons were extracted for mechanical and metallurgical testing.

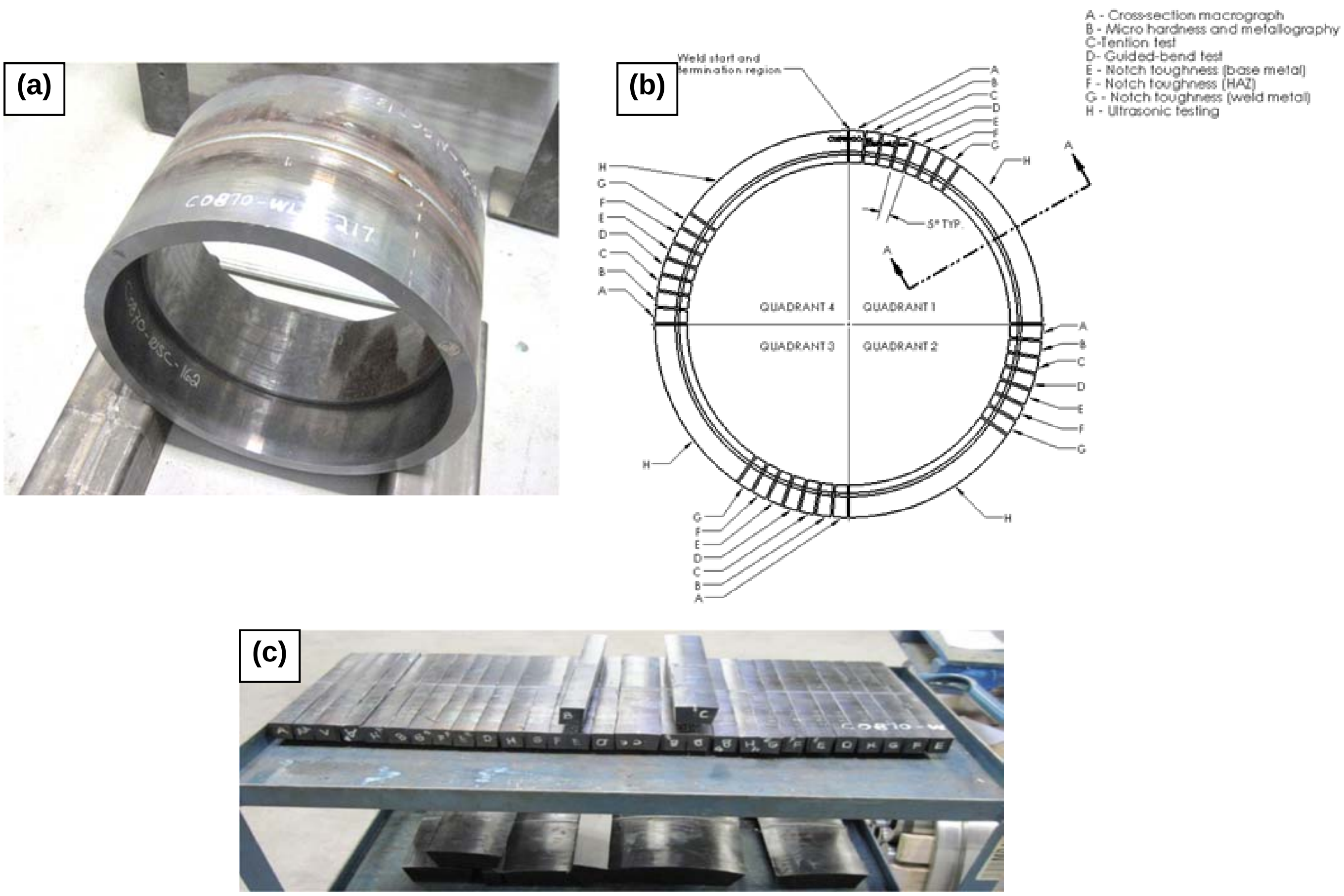


Figure 3.3: (a) UFC Closure Weld Mock-up Assembly Simulating Shell-to-Head Geometry for WPS/PQR Testing, (b) Sampling Locations and (c) Coupons for Mechanical/metallurgical Tests

The ASME Code requires tensile, Charpy impact, and guided bend testing of weld metal, heat affected zone and base material. NWMO supplementary testing included microhardness, microstructure, weld penetration and ultrasonic examination. Novika was able to successfully qualify a weld procedure to meet or exceed ASME Code standards and also meet NWMO's supplementary requirements. NWMO utilized two external welding engineers to review and verify the acceptance of the WPS and PQR documents.

To demonstrate the leak tight nature of the HLAW closure weld procedure, Novika was tasked with performing a helium leak test on a UFC mock-up welded assembly. The helium leak test was to be carried out in accordance with ASME Section V, Article 10, Appendix IV (Detector Probe Technique). The test assembly was designed and constructed by Novika (Figure 3.4). Three assemblies were fabricated and tested. During the inspection, each component was purged with helium gas to obtain a helium concentration of at least 90%, and then pressurized with helium to 50 psi (3.4 bar) for at least 30 minutes. The helium detection probe was then passed along the weld on the full circumference to search for leaks. The assemblies showed no detectable leak, ensuring the closure weld process results in a leak free joint.

Figure 3.4: Helium Pressurizing of UFC Closure Weld Mock-up Assembly

3.2.1.2 Non-Destructive Examination (NDE) Development

In 2015 the vendor Nucleom Inc. commenced work on the development of Non-Destructive Examination Procedures for the inspection of the UFC closure welds and external copper coating. The detailed objectives of the program are as follows:

- Develop NDE techniques, using appropriate methods, equipment, and probes for the detection and sizing of weld defects (volumetric and surface) and measurement of design characteristics (penetration depth) on partial penetration weld test coupons and UFC mock-ups fabricated by HLAW welding technology.

- Develop the NDE techniques, using appropriate methods, equipment, and probes for the detection and sizing of defects (volumetric, surface, and dis-bond) and measurement of coating thickness in electrodeposited “bulk coating”, cold spray “closure zone” and electrodeposited / cold spray “transition zone” samples (flat plate and UFC mock-ups).

Nucleom initiated this program by preparing a detailed NDE Design & Development Plan. The plan, summarized in the flowchart shown in Figure 3.5, includes code & standard requirements, definition of applicable inspection methods, list of samples to be used for development of examination techniques, probability of detection (PoD) analysis, creation of a defect catalog and definition of the NDE inspection system/procedures for the weld and copper coating inspection programs.

Review of the appropriate codes led to the selection of phased array ultrasonic testing (PAUT) (see Figure 3.6), time-of-flight diffraction (TOFD) and eddy current testing (ET) as the examination methods to be considered for both closure weld and copper coating inspection. Review of the codes also led to a preliminary target flaw size (TFS) for detection. Test samples for closure welds and copper coating (electrodeposited, cold spray and transition zone) were manufactured by NWMO's respective technology vendors and provided to Nucleom for the fabrication of calibration standards. These calibration standards incorporate a wide range of NDE artificial reflectors, representing potential flaw types and sizes. In 2015, calibration standards for weld inspection were completed and copper coating reflector samples were still in production. Progress in this program shall be reported in 2016.

Acoustic ray tracing, beam simulation and depth of penetration calculations were performed to determine the initial inspection configuration for the selected inspection techniques. Using these baseline parameters, experimental development trials were conducted and the following conclusions were made with respect to the closure weld:

- A combination of ultrasonic techniques (PAUT and TOFD) was shown to provide increased detection and sizing capabilities. Using two independent methods provides additional confidence in the results when flaws are detected with both techniques. PAUT is effective for locating defects but TOFD is often required for characterization and sizing of these flaws.
- Best results were obtained with 10MHz transducers for both PAUT and TOFD.
- The selected NDE techniques can achieve a 100% volumetric coverage of the weld.
- Eddy current proved to be an efficient detection and sizing tool for surface breaking flaws.

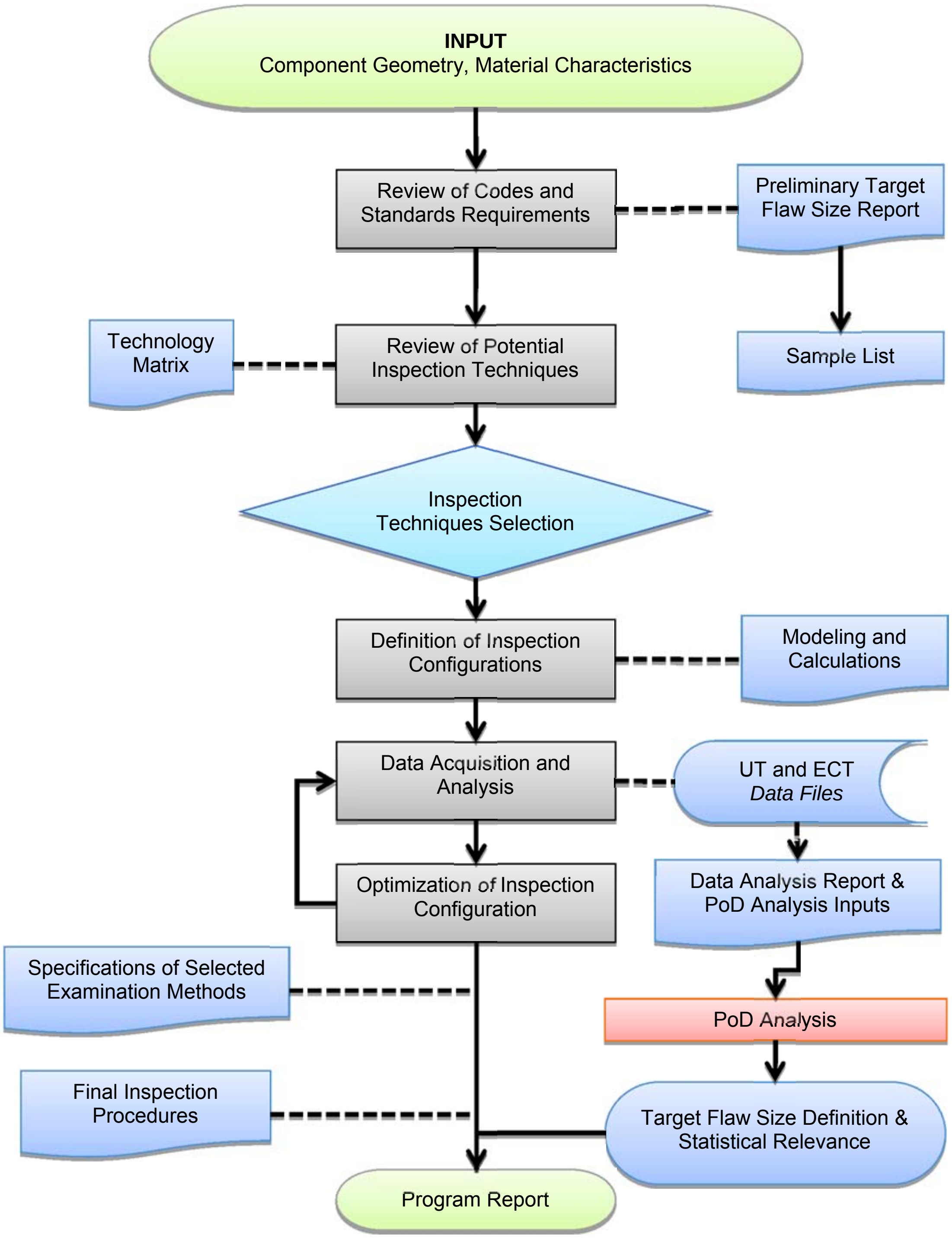


Figure 3.5: Design Development Process Flowsheet for Non-Destructive Examination program

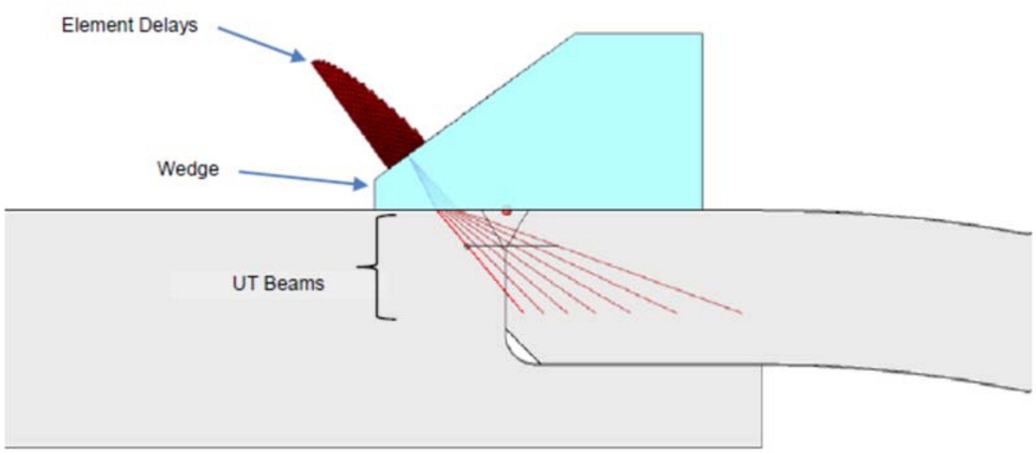


Figure 3.6: Beam Simulation of Shear Wave Phased-Array-Ultrasonic-Testing (PAUT) Applied to Mark 2 Closure Weld / Joint Configuration

Details from the technique development trials were input into the closure weld PoD program; this work is ongoing.

3.2.1.3 Prototype Fabrication

The development and demonstration of an optimized machining process plan is critical aspect of manufacturability for the Mark 2 UFC and has implications on component design, assembly and finishing operations for both steel core and copper coating elements of the vessel. As part of the UFC Manufacturing Development, NWMO has a dedicated UFC Machining Program to address these issues. This program will incorporate established criteria from the HLAW closure welding and copper coating programs as they pertain to dimensional requirements and create a sequential plan and associated process/drawings to facilitate machining of separate components, welded UFC assemblies and the final copper coated vessel. Output from this program will allow NWMO to optimize the container design with respect to machining tolerances.

In 2014 NWMO's selected vendor, Niagara Energy Products (NEP), prepared a Machining Process Plan which describes the equipment, operations, inspection, and examination processes required to machine the UFC. In 2015, NEP began the implementation of this plan by commencing the production of steel shell and hemi-head components for 6 prototype UFC's. The first manufacturing campaign supplied components (Figure 3.7) for 2 UFC's which were subsequently forwarded to Novika for welding of the lower assembly (i.e., shell and lower head). The lower assemblies and upper heads will be copper coated by electrodeposition in 2016 and then returned to NEP for copper coating machining. Information regarding dimensional tolerances and lesson learned shall be incorporated into the second machining campaign scheduled for mid-2016.

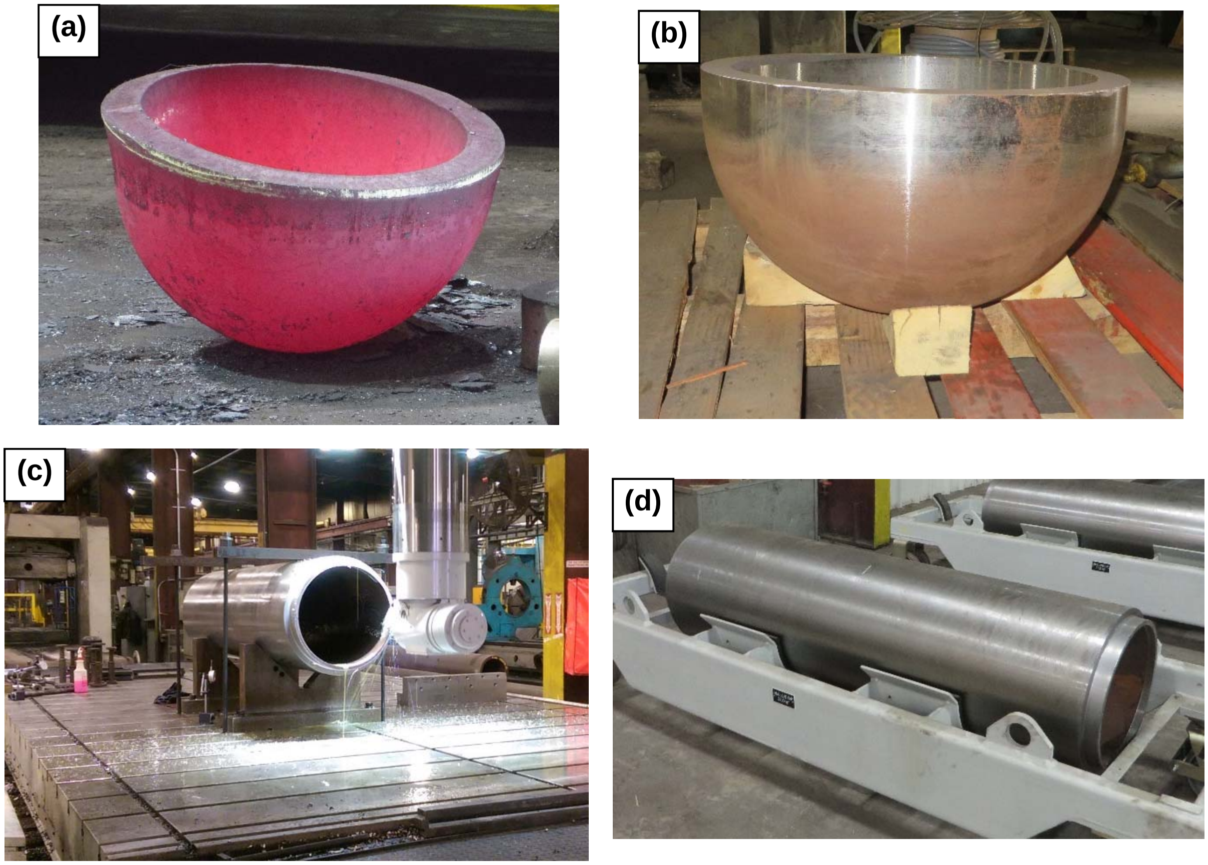


Figure 3.7: Mark 2 Steel Shell and Hemi-Head Components Fabricated as Part of UFC Machining Program. Hemi-head in (a) as-formed Condition and (b), After Intermediate Machining Step. Shell During Machining (c) and, (d) in Final Configuration

3.2.2 Used Fuel Container Structural Testing

A full-scale external pressure test of a prototype Mark 2 was completed in collaboration with Penn State Advanced Research Lab (ARL) High Pressure Test Facility (HPTF) as a way to experimentally validate the computer modelling analyses and prototype manufacturing techniques. 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 container during the next ice age.

This is the first of several planned pressure tests. The key objectives of this initial test include:

1. Determine the buckling collapse load of a prototype steel-only Mark 2 UFC
2. Execute the preliminary test methodology (calibration test)
3. Establish lessons learned and improvements for future tests

In order to securely handle and manipulate the container, a custom lifting fixture that can also withstand the immense testing pressures was designed and fabricated. The fixture, shown in Figure 3.8: has four removable cross-bars; three on the top and one on the bottom. All cross-bars are installed for secure shipping of the UFC. Prior to testing, the upper and lower crossbars at the center of the fixture are removed because computer modelling predicted that buckling will initiate at the mid-shell. Tight confinement in this area could lead to damage of the fixture or unduly influence the buckling load.

Figure 3.8: Used Fuel Container Fixture Configured for Testing

The container was instrumented with strain gauges to record the deformation of the container in real time as the external pressure was increased. The gauges underwent a potting process to protect the circuity from water ingress, as shown in Figure 3.9: .

Figure 3.9: Strain Gauges Potted Onto the Used Fuel Container (UFC) at Closure Weld Location

The fixture and container were then lowered into the pressure test vessel, as shown in Figure 3.10. The ARL's HPTF largest pressure vessel can test objects up to 1.5 meters in diameter and 4.2 meters long, up to a pressure of 110MPa. This pressure is equivalent to the water pressure experienced at the bottom of the Marianas Trench approximately *11 kilometers* deep – the deepest location on the planet. Figures 3.10 to 3.13 show the remaining steps for hooking up the strain gauges and securely closing the pressure vessel prior to testing.

Figure 3.10: Vertical Orientation and Emplacement Into The Pressure Vessel

Figure 3.11: Moving Lid Into Position

Figure 3.12: Lid Retaining Ring Installed

The container was then tested three separate times. The first stage of testing was a monotonic pressure increased to ~15MPa (test target of 2250psi or 15.5MPa); this pressure represents the conservative maximum normal load that would occur in the repository due to hydrostatic head and the buffer swelling pressure. This pressure was held for 10 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.

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 3000m thick glacier, as well as the additive effect of the buffer swelling pressure. This pressure was held for 10 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.

The third stage and final stage of testing was conducted in two phases. The first phase was a monotonic pressure increased to ~45MPa (test target of 6650psi or 45.2MPa). This pressure was held for 10 minutes. This was followed by a slow monotonic rise to ~8000psi (55.2MPa), which was held for about 5 minutes. The re-check was performed at this pressure because the computer modelling, completed prior to the testing, suggested that failure would occur at minimum of ~55MPa. This pressure milestone meant that failure could occur at any time. The pressure was then increased at a slow rate (~25psi/minute) until failure. The mode of failure, buckling collapse initiated at the mid-shell, occurred at ~57.2MPa, within the expected range for the container.

In conclusion, the Mark 2 UFC prototype behaved as expected. It easily withstood the maximum theoretical pressure that could be exerted on the container under a worst-case scenario during the next ice age. This testing not only demonstrates the suitably of the design but also proves out the fabrication including material selection, machining, and welding. For future work the tests will be repeated with a copper coated Mark 2 UFC prototype to demonstrate the robustness of the copper coating corrosion barriers.

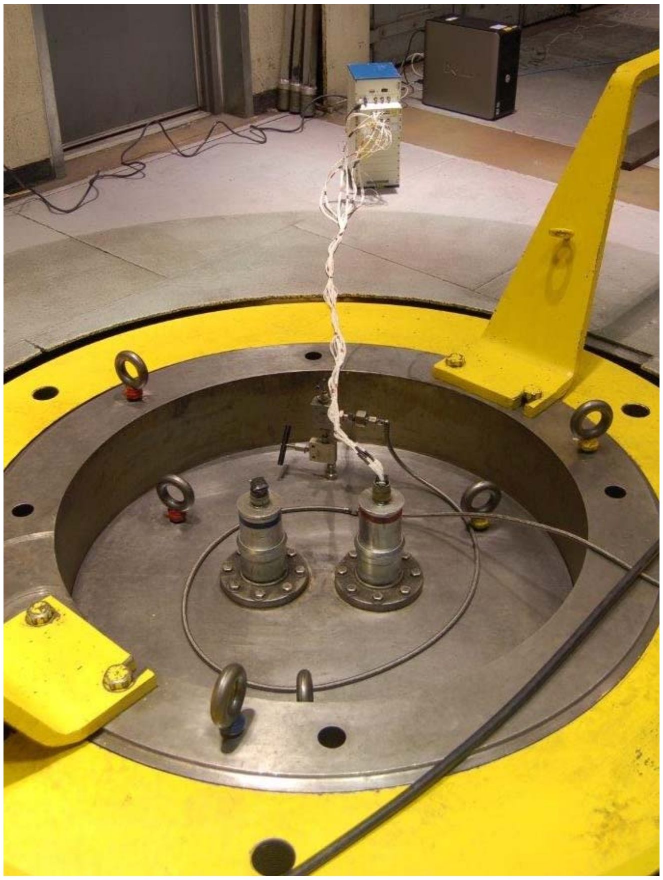


Figure 3.13: Final Closure Complete. Through-wall Connectors Attached to Data Acquisition System

3.2.3 Used Fuel Container Copper Coating Development

In 2015, NWMO continued the development of copper coating technologies for the UFC external surface corrosion barrier. This effort included optimization and scale-up of both electrodeposition and cold spray processes for the application to prototype UFC's.

3.2.3.1 Electrodeposition

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

In 2015, Integran produced the first full-size UFC lower assembly (shell welded to the lower hemi-head) utilizing a proof-of-concept electroplating line. Figure 3.14 demonstrates the processing of the lower assembly through three phases of the electroplating cycle: as it is immersed into the cleaning bath, as it emerges from deposition of an initial layer, and as a finished product.

Following the successful coating of the initial component, NWMO initiated a program to continue to production of additional copper coated hemi-heads and lower assemblies, as well as a range of test samples to support other programs. These include electrodeposited copper coating samples for corrosion testing, cold spray transition zone application, NDE samples and mechanical testing.

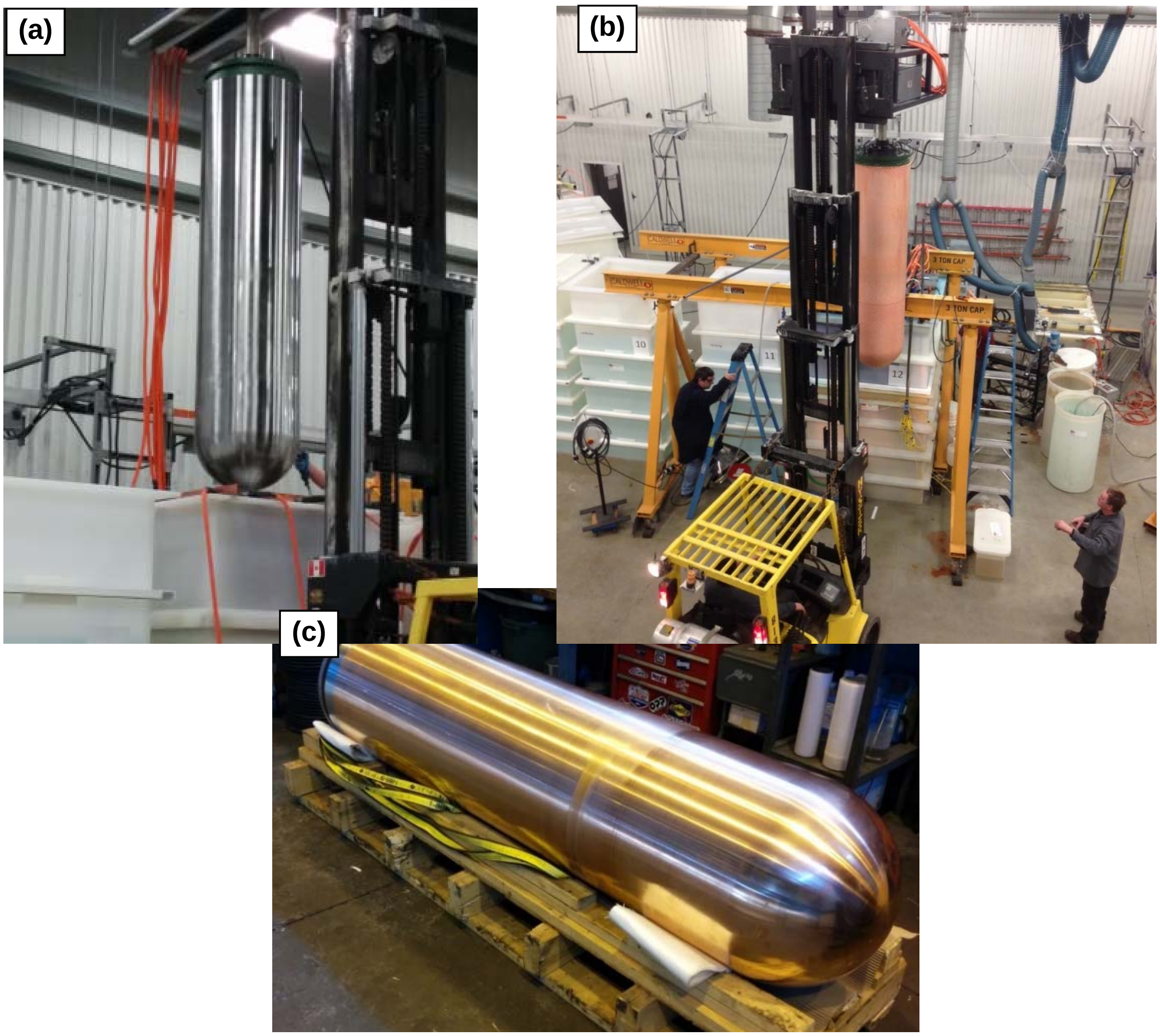


Figure 3.14: Electrodeposition of Copper on a Full-Sized UFC Lower Assembly : (a) Steel Part Being Immersed into Cleaning Solution; (b) Following Deposition of Initial Copper Layer; (c) Coated and Machined

As noted above, NWMO has utilized a proof-of-concept electroplating line at Integran for development to date. In support of NWMO's Proof Test Program, NWMO contracted a process engineering firm (Integrated Technologies Inc) to prepare a design package for an optimized Electroplating Pilot Cell Facility ("Facility"). This Facility, shown in Figure 3.15, would be used for further optimizing, testing and demonstrating the capability of the electrodeposition process copper coat UFC's under simulated serial production.

In a parallel effort, the preliminary assessment of an alternative copper electrodeposition technology using sulphate bath chemistry and horizontal plating (barrel plating) was conducted with the vendor BEP Surface Technology.

International efforts were bolstered by the fabrication of small copper tubes for the collaborative program in the Grimsel Test Site, MaCoTe. Within this program, the Czech collaborators developed a design for the emplacement of test modules into boreholes in the Swiss granitic rock laboratory. NWMO provided the samples illustrated in Figure 3.16; the figure also shows the module being assembled with steel samples and as-assembled and ready for emplacement (i.e., with its casing).

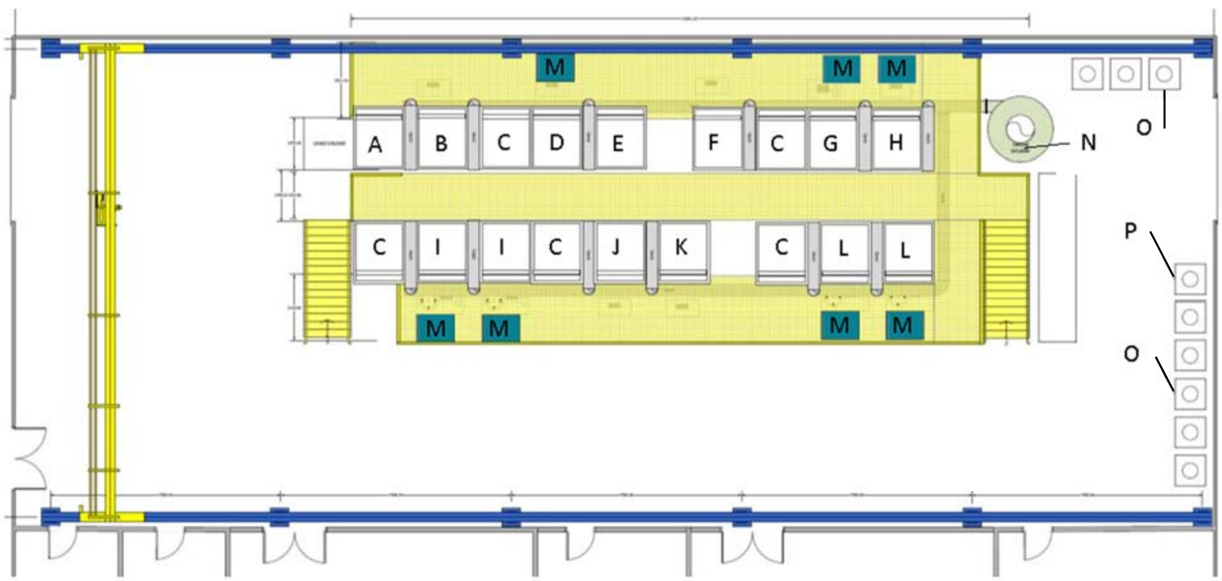


Figure 3.15: Layout of an Optimized Electroplating Pilot Cell Facility for Copper Coating UFC's: (A) Hot Rinse, (B) Soak Clean, (C) Spray Rinse, (D) Electroclean, (E) Immersion Rinse, (F) Pickle [acid salts], (G) Electropolish, (H) Nickel Strike, (I) Copper Plate [Nanovate], (J) Microetch, (K) H2So$_4$ Dip, (L) Cyanide Copper Plate, (M) Rectifier, (N) Vertical Scrubber, (O) Process Chemicals Tote, (P) Wastewater Tote

Ongoing electrodeposition work includes an extensive optimization program of the electrodeposition process, such that a manufacturing specification can be developed and applied for demonstration of serial manufacture.

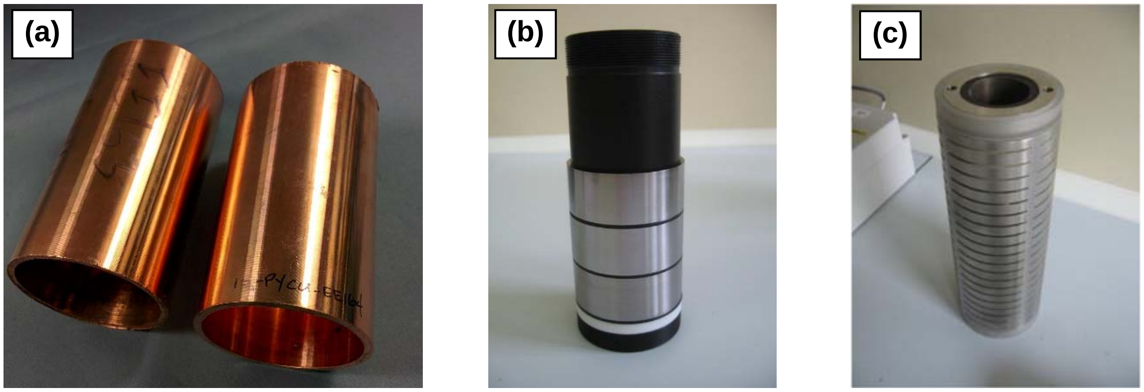


Figure 3.16: Collaborative Analysis Program MaCoTe Components, Including (a) Electrodeposited Copper Samples; (b) A Test Module That Has Been Partly Assembled Using Steel Samples; (c) A Complete Module Ready For Emplacement in the Grimsel Test Site

3.2.3.2 Cold Spray

Following the successful development of a copper cold spray method to completely coat UFC components (hemi-heads, lower assembly) in 2012 and 2013, NWMO focussed on the adaptation of the technique to the UFC closure weld zone. This region is the portion of the UFC that is uncoated prior to the loading of used fuel inside the used fuel packing plant; the zone undergoes closure via HLAW welding. Following closure and inspection via NDE, the coating of this region via 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 (Figure 3.17), significant optimization was required prior to implementing this method. This work has 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.

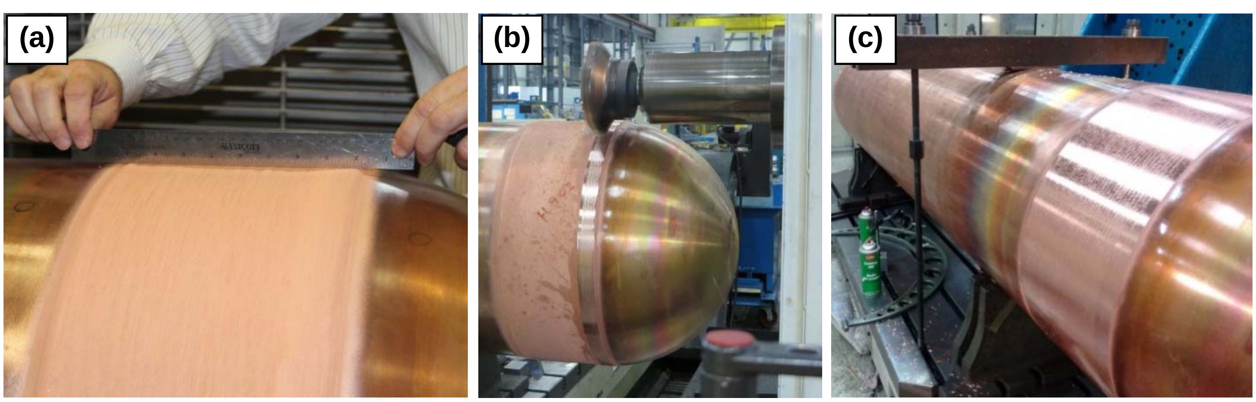


Figure 3.17: Cold Spray Copper Coating Applied to Closure Weld Region (a) Before (b) During and (c) After Machining

To complement the applied research noted above, the NWMO has also contributed to fundamental research on the topic of cold spray with its research partner, the National Research Council. This strategic initiative promises to strengthen the Canadian expertise in cold spray processes, producing more highly qualified personnel and contributing to the industry as a whole. These goals align well with NWMO's long-term plan to utilize a mature cold spray process during DGR operations.

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 UFCs in a DGR. This extensive program considers a wide range of scenarios, and has been developed to further the understanding of the chemistry that will exist, as well as to lower the uncertainty within the prediction of the performance of the UFC. Specific topics are described below, and additional corrosion-related work is being performed as part of the microbial assessment program and within the international experiments that are ongoing at both the Grimsel Test Site and Mont Terri in Switzerland.

3.2.4.1 Corrosion of Copper Coatings

With the development of copper coatings, it has become necessary to investigate different copper forms to ensure that corrosion does not occur preferentially via mechanisms that do not occur for wrought coppers. Because thermodynamic arguments are used (as opposed to kinetic arguments) to describe the ability of copper to have a very long life in the repository, there is little risk of this occurring in a general sense, but there is a possibility that localized effects may differ among copper species, in principle. Western University has done extensive work in this area, including:

- Long-term exposures of copper samples;
- Electrochemical polarizations to simulate corrosion;
- Various exposures of galvanically coupled steel and copper samples to simulate damaged containers; and
- Comprehensive surface analysis to assess samples before and after the exposures noted above.

Despite more than three years of effort, little difference can be found among the samples. Very slight differences can be seen only where extensive cycles of electrical currents to initiate copper oxidation (i.e., corrosion) are used. In these experiments, there is some weak evidence that the copper coatings made by electrodeposition or cold spray undergo a very minor preferential grain etching, such that corrosion depth may be very slightly greater near grain boundaries. Studies are ongoing to quantify this depth, which at present appears to be a few micrometres (and thus, insignificant to the safety of copper coatings on the order of 3 mm thick). An upcoming publication in a peer-reviewed journal will provide a comprehensive description of the most current understanding of copper coating corrosion.

3.2.4.2 Corrosion of Copper in Groundwater/porewater

For copper within the anoxic conditions of a DGR, a very long life is expected. For a 3 mm barrier, greater than one million years of stability is expected. Despite the thermodynamic evidence that supports this, NWMO has a very active program investigating copper corrosion for a range of conditions that may or may not be present in a DGR.

Of particular note is the high salinity exposure case, which may occur for copper in Canadian sedimentary formations where chloride salinity may range 3 - 5 mol/L. The equilibrium is described by equation [i].

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

for n = 2,3.

As the process is presented, the forward reaction (i.e., corrosion of copper) can be suppressed by very small amounts of hydrogen or copper chloride species in solution or elevated pH. Typically, the reaction is not expected to be significant in neutral or basic conditions.

In principle, a similar equation may be written to describe aqueous copper in the absence of chloride, as per equation [ii]:

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

Experiments that attempt to characterize such a reaction struggle to identify copper-hydroxide products. From the copper interaction with water, it is well known that a small amount of Cu_2O will form at the copper surface, but the production of any measurable amount of this species or the presence of small amounts of hydrogen will inhibit this reaction.

As noted above, for both fresh and saline conditions, the equilibria strongly favour the metallic copper as opposed to the corrosion products, based on thermodynamic evidence. NWMO has had a program investigating these processes for many years via the detection of extremely small amounts of hydrogen. The experimental schematic is shown in Figure 3.18. For this device, trace hydrogen is collected every 14 days from the headspace in a Tedlar bag.

Continuing from the experiments of previous years, the release of hydrogen has been correlated with small equivalent corrosion rates over many months/years of data collection. For mildly acidic conditions (pH 4-5) at elevated temperature (i.e., 75°), rates typically range between 2 and 4 nm/a for the saline exposure case, and typically below 2 nm/a for neutral conditions (pH 6-7). Reduction of exposure temperatures to 50°C produces lower rates, between 0.2 and 0.6 nm/a; the highest rates occur for the lowest pH, and neutral pH produce the lowest rates. Negligible rates are measured for exposures conducted at 30°C.

Where temperatures were varied within the experiments, using month-long holding points of 30, 50 and 75°C in random orders, rates of 10 nm/a are measured for the pH 4-5 conditions, but only during the 75°C exposure period. Temperatures above 90°C also yield an increase in release of hydrogen, similar to the cycles up to 75°C. After several months, these cells ceased producing hydrogen completely, and only nominal amounts of hydrogen were subsequently produced, even after very long exposures to 75°C solution.

For pure water conditions, corrosion rates were generally lower, never exceeding 1 nm/a for the pure water, neutral pH and 75°C conditions. During a temperature elevation above 90°C, a hydrogen spike produced equivalent corrosion rates as high as 4 nm/a. However, hydrogen evolution was permanently suppressed for copper when temperatures were elevated to 75°C for very long periods of time.

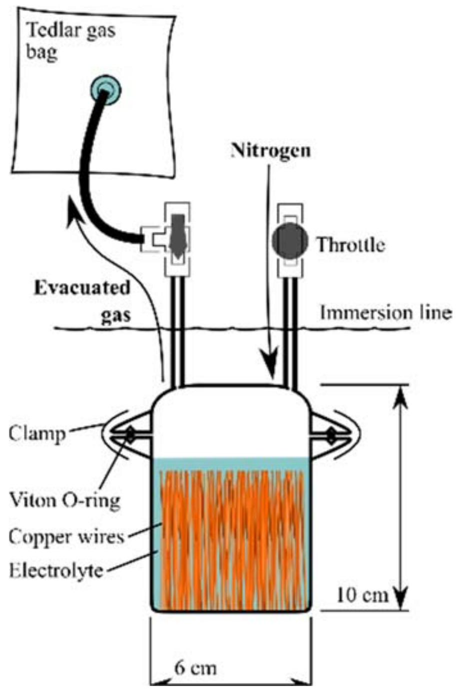


Figure 3.18: Schematic of The Experimental Cell Used for Sensor-monitored Experiments

Notably, these values were all measured in the absence of clay/bedrock barriers, where hydrogen was continually removed and quantified, forcing the reaction in the direction of the corrosion reaction. They are not true corrosion rates, as evidenced by the complete shutdown of the mechanisms when temperatures were elevated above 90°C. They are useful as bounding values to assess the maximum amount of copper loss by these processes. Even conservatively presuming elevated temperatures of 75°C for as long as 10,000 years, and 50°C for another 90,000 years, copper loss would be restricted to < 0.1 mm via these mechanisms; losses would be further reduced via the slow transfer of corrosion products within the bentonite.

3.2.4.3 Corrosion of Copper in Sulphide/Chloride

Although copper can be corroded when it is exposed to sulphide-containing solutions, the very dilute concentrations of sulphide found in Canadian groundwaters offer little probability of corrosion within tens of millions of years. Nonetheless, this active system requires a thorough understanding of the mechanism of sulphide-induced corrosion, particularly in the presence of other groundwater species (such as chloride), where synergistic effects have been hypothesized. For dilute to moderately concentrated (i.e., 1 mMol/L to 0.5 mol/L) chloride/sulphide systems, extensive work by SKB (of Sweden) has shown that no synergy exists: neither chloride nor sulphide enhance each other’s corrosion rates. While the high salinity of the Canadian sedimentary sites is not covered by these studies, the sites are virtually sulphide free, and have almost no water present: therefore, there is little risk of sulphide/chloride corrosion for these sites. Nonetheless, to supplement ongoing SKB work, NWMO initiated a new study in 2015 to investigate high chloride conditions over a range of sulphide concentrations to further the mechanistic understanding behind these processes. Results are expected to be produced by the end of 2017.

3.2.4.4 Corrosion of Copper in the Presence of Radiation

Owing to the presence of the radioactive fuel within the UFC, some amount of gamma radiation is expected to penetrate the vessel and interact with incoming water from the DGR. While this dose is small (i.e., < 4 Gy/h assuming water immediately ingresses to the UFC) and decays rapidly when compared to the repository (i.e., < 1000 a), gamma radiolysis of water is a well-known phenomenon. The net effect of the interaction between radiation and water is to produce a range of species of varying oxidizing and reducing potentials, including hydrogen peroxide, oxygen, hydroxyl radicals, as well as hydrogen atoms, molecular hydrogen and solvated electrons. Literature analysis indicates that the low dose rate will not cause any additional corrosion, and may in fact be very slightly protective for copper in a DGR. Ongoing research supports this assessment, and has also led to some insight on the process by which corrosion may occur. This program combines NWMO participation and funding with expertise from two faculty members at Western University, experimentation at Chalk River of the Canadian Nuclear Laboratory, and funding by the Natural Science and Engineering Research Council (NSERC) in the form of a Collaborative Research and Discovery Grant.

Similar to many of the NWMO programs, these insights are gained by creating conditions that are more aggressive than what is expected for a DGR; in this case, radiation doses are augmented by unrestricted air inflow (versus the anoxic DGR which will quickly exhaust oxygen), and water is unevenly distributed on the copper surface. The experimental set up is shown in Figure 3.19.

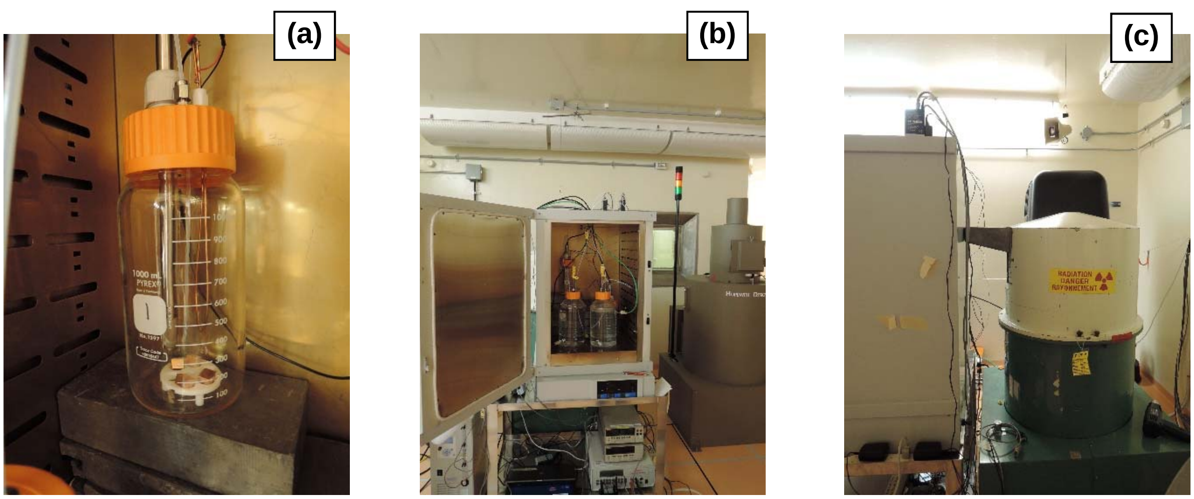


Figure 3.19: Vapour Phase Copper Radiolysis Cell Showing (a) Copper Samples at the Base of the Sample Vessel (b) Sample Vessels Loaded Into Exposure Oven and (c) Radiation Source at the Back of the Oven

Results from this program reveal that the corrosion induced by the combination of air, radiation and water vapour does not tend to cause significant damage to the surface. The effect of the low dose of radiation is also very small; samples are little more corroded with radiation present than they are in the absence of radiation. The aspect ratio of corrosion depth versus corrosion area is also very low; typically less than 1:100 is observed.

3.2.4.5 Consequences of Corrosion of Steel inside a Used Fuel Container

As reported previously, the NWMO initiated a program to study the effects of internal corrosion phenomenon, including where trace amounts of oxygen and water are present along with ionizing radiation from spent used nuclear fuel. A likely outcome for trapped oxygen and water includes producing a general corrosion product universally inside the UFC; the calculated thickness for such species is 1-2 µm. Should corrosion localize instead, additional damage may occur in isolated regions; this could, in principle, result in a container with a reduced localized wall thickness. Early results from this program indicate that general corrosion is the preferred mechanism of consuming trapped water and air. However, to ensure the integrity of the container and understand all possible mechanisms that may occur internally, the NWMO has partnered with the University Network of Excellence in Nuclear Engineering (UNENE) to fund a five year Industrial Chair Research program to investigate this and related corrosion reactions. With matching funds by NSERC, this program offers an opportunity to contribute to NWMO design and safety analysis, as well as fundamental research in the field of radiation corrosion chemistry.

3.3 BUFFER AND SEALING SYSTEMS

In 2015, the NWMO continued with several buffer and sealing systems programs, including: the fabrication of Highly Compacted Bentonite (HCB) blocks, the demonstration of Gap Fill placement, the demonstration of the Buffer Box Assemblage, and the continued assessment of the variability of properties of bentonite-based sealing materials.

The purpose of the variability study was to provide data on the bentonite buffer to support the placement room design. Bentonite is a naturally occurring material, and so its properties may potentially vary. The NWMO initiated a program to characterize a representative sampling of commercially available Wyoming bentonite for thermal conductivity, hydraulic conductivity, swelling pressure and other index properties. This program is required to assess whether the manufactured buffer and backfill will meet NWMO performance requirements for a range of potential groundwater geochemistry.

In 2015, the NWMO assembled the Buffer Box Demonstration Unit (Figure 3.20) using bricks (≈ 0.36 m by 0.1 m by 0.1 m), produced by the NWMO Brick Maker. The bricks were subsequently trimmed and placed along with the prototype UFC into the Buffer Box shell to simulate a full scale Buffer Box. The assemblage represented a development platform for future work on large scale blocks, as well as, understanding the component interfaces of the Buffer Box.

Figure 3.20: Buffer Box Demonstration Unit

3.3.1 Isostatic Compression of Quarter and Full Scale Bentonite Blocks

Building on the experience of manufacturing bentonite bricks, NWMO embarked on a program of block fabrication using an isostatic press. Initially, a ¼ scale block was pressed to gain experience with the manufacturing process and to verify that the dry density requirement of 1.7 g/cm^3 is achievable.

Caldic Canada Inc. was contracted to supply pre-blended MX-80 bentonite with a moisture content of 20%. The bentonite was then loaded into an isostatic press bag (Figure 3.21a) and container supplied by the Trexler Rubber Company of Ravenna, Ohio. The bag was sealed and shipped to the Advanced Research Lab (ARL) at Pennsylvania State University (in State College, Pennsylvania) to be pressed into the 60 inch pressure vessel.

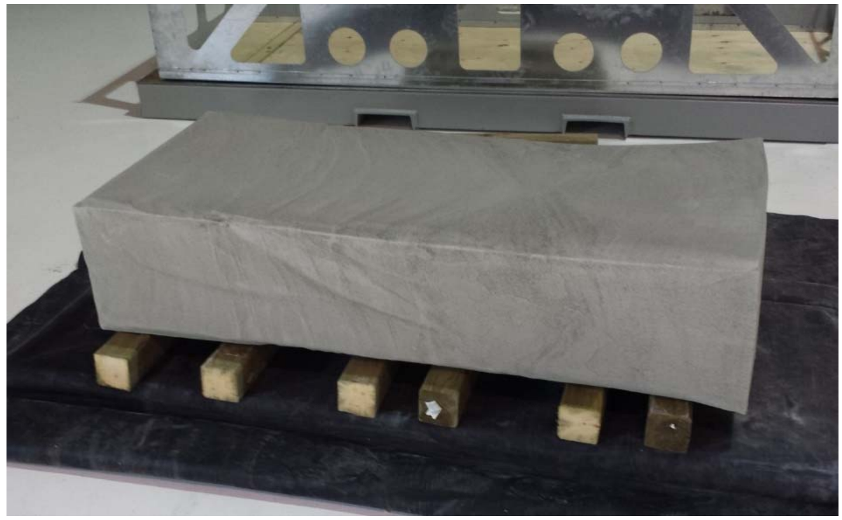



Figure 3.21: a) Isostatic Bag and Container (left) and b) Highly Compacted Bentonite Block (right)

The ¼ scale block (Figure 3.21b) was sampled once returned to the NWMO. Eighty-nine core samples were measured and weighed and the average dry density was 1.745 g/cm^3. Additional samples were submitted to AMEC Foster Wheeler for testing and these results also verified that dry density requirements were met. The successful ¼ scale trial resulted in expediting scaling-up to a full-size block, one that would form one half of the NWMO Buffer Box Concept.

The same vendors were utilized to facilitate two full-size blocks in 2015. The isostatic container for the full size block (Figure 3.22) was designed so that it could be disassembled into 4 pieces to facilitate block removal. The container is made from structural steel and weighs 2688 kilograms. It is 3.86 meters tall and designed to fit the 60 inch (inside dimension) press at the Advanced Research Lab (ARL) at the University of Pennsylvania. To ensure the bag would be properly filled, with no folds or voids, a vacuum can (Figure 3.23) was integrated on the outside of the container to aid in filling. Applying a vacuum pulls the bag tightly against the inside of the container.

Figure 3.22: Full-size Block Isostatic Container

The loaded container was shipped to the Pennsylvania State ARL and the blocks pressed (on separate dates). Both blocks were pressed without incident and shipped back to the NWMO Oakville facility for inspection (See Figure 3.24 and 3.25). Each block weighed approximately 4000 kg. Both blocks were tested in the same manner as the ¼ scale block to verify moisture content and dry density. The average dry density of the first block was 1.748 g/cm^3 at a moisture content of 20.03% and the average dry density of the second block was 1.738 g/cm^3 at a moisture content of 20.40%. Both blocks exceeded the 1.7 g/cm^3 dry density requirement as expected.

Figure 3.23: Vacuum Can Assembly

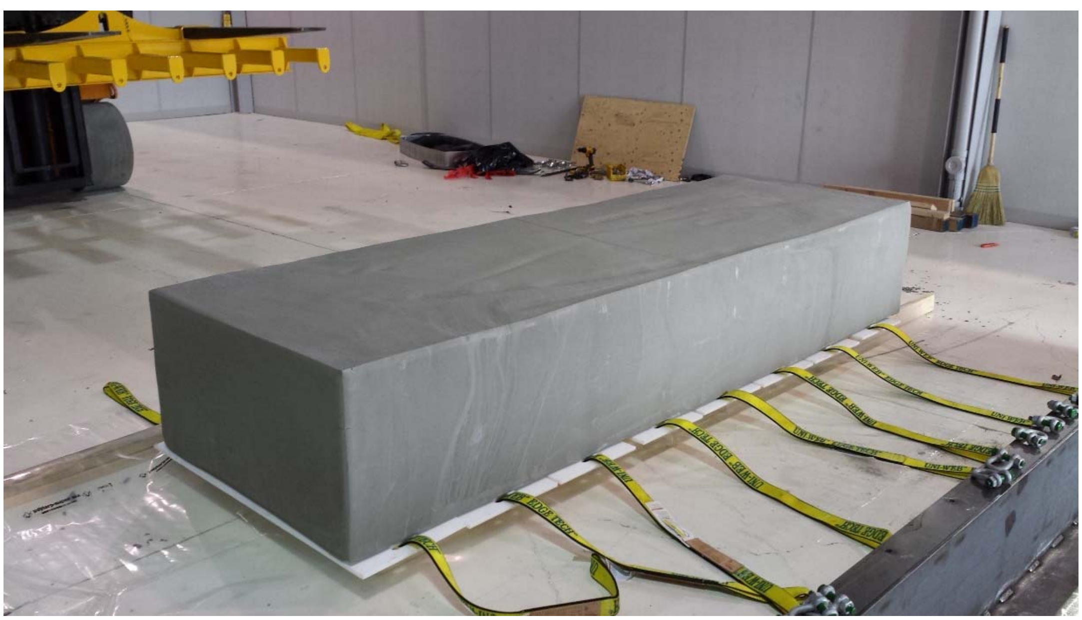


Figure 3.24: Block #1 Unwrapped

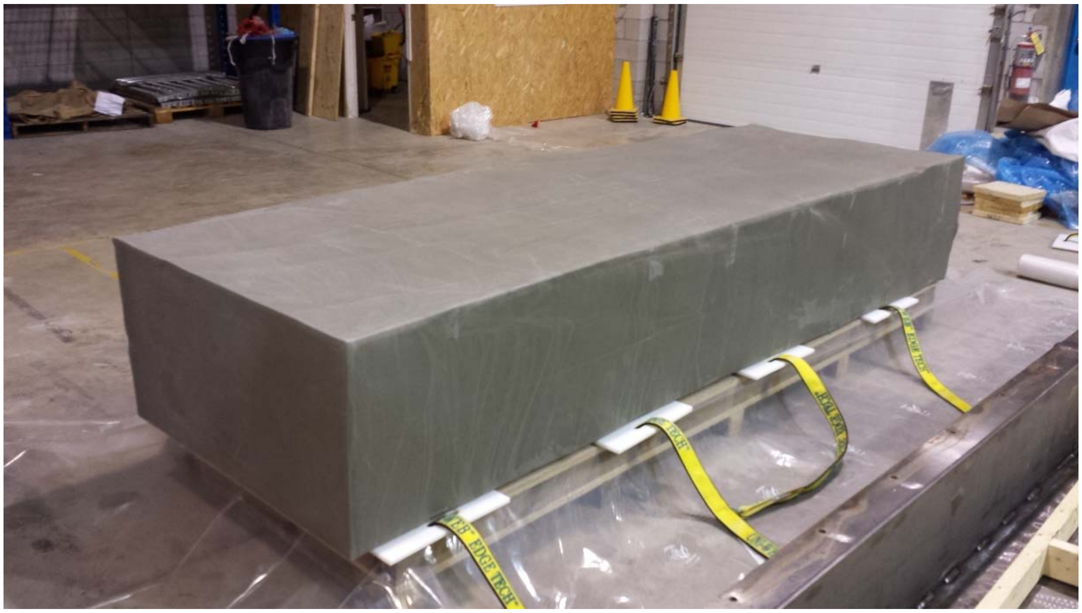


Figure 3.25: Block #2 Unwrapped

3.3.2 Highly Compacted Bentonite Block Shaping

In 2015, the NWMO also investigated shaping the Highly Compacted Bentonite blocks pressed at the Pennsylvania State ARL. Preliminary trials were performed in the summer on a small piece taken from the ¼ scale block to assess the feasibility of shaping at a local vendor (Figure 3.26). Automated stone shaping technology was used to square the block and hollow the cavity that would accommodate the used fuel container. The success of the small scale trial allowed NWMO to scale up to a full-size block (Figure 3.27).

Figure 3.26: HCB Shaping Trial

Figure 3.27: Full Size HCB Block Shaping Trial

3.3.3 Small Scale Gap Fill Testing Program

Small Scale Gap Fill placement trials were carried out to demonstrate that Gap Fill-like materials can fill a void that simulates the gap between the rock walls of the Placement Room and the stacked Buffer Boxes and Spacer Blocks, while achieving an equivalent dry density that meets or exceeds the Gap Fill Material (GFM) performance requirements of 1.41 g/cm^3.

The Gap Fill-like materials were delivered from a hopper to the gap through an auger, as shown in the photographs in Figure 3.28. In these trials, the material was placed in layers of different thicknesses, and methods were used to densify the placed GFM such as by applying vibrations and/or inserting the auger nozzle into the placed material. In these demonstrations, the as-placed dry density of the GFM was found to meet design requirements. These trials also provided a learning platform for full-scale trials that will be conducted in 2016.

Figure 3.28: Photographs of a) Utility Auger and Test Frame and b) Utility Auger filling the 4th layer

3.3.4 Microbial Studies of Repository Sealing Systems

NWMO maintains a work program that integrates microbiological, geochemical and modelling activities to provide evidence that microbiologically influenced corrosion (MIC) will not compromise the used nuclear fuel container. This work is achieved through: i) international partnerships at the Grimsel and Mont Terri Underground Rock Laboratories in Switzerland; ii) experimental programs at the University of Saskatchewan and Ryerson University; and iii) diffusive modelling of microbially-produced species by York University.

NWMO is participating in the Grimsel Underground Laboratory (URL) Materials Corrosion Test (MaCoTe) in Switzerland. The MaCoTe project involves lowering modules containing metal coupons and Hard Compacted Bentonite (HCB) into boreholes (~9 m deep) and then retrieving them over a period of several years. The overall goal is to demonstrate that highly compacted bentonite can inhibit microbial activity in situ and mitigate MIC of the used nuclear fuel container (Figure 3.29). NWMO is leading the efforts to characterize microbial communities and groundwater geochemistry of the borehole through programs supported at the University of Toronto and McMaster University. Methods are also being developed to extract and analyze biological compounds (nucleic acids, phospholipid fatty acids) from within the rock matrix itself in order to characterize microorganisms that may exist within the rock matrix. Understanding the geochemistry and natural microbiological conditions in the boreholes provides important information about the initial conditions in situ and is a benchmark to compare results from retrieved bentonite. In the Fall of 2015, researchers from the universities of Waterloo and Saskatchewan obtained bentonite samples from a module retrieved from the borehole after one year, and sample analysis is ongoing

NWMO continued to support the Microbial Activity (MA) and Hydrogen Transfer (HT) experiments at Mont Terri. A multi-year, multi-laboratory investigation of in situ microorganisms in the Opalinus Clay finished as part of the MA experiment. The results indicated that while it is possible to extract DNA from the Opalinus Clay, considerable heterogeneity in the distribution of microorganisms may exist. Overall, this work warrants further investigation using a broader range of DNA extraction strategies, and DNA amplification approaches. Variability in sequencing efficiency may also be explored as part of future work. NWMO continues to sponsor the HT experiment. The objectives of HT include: i) evaluating the effective diffusion coefficient of hydrogen in the Opalinus Clay; ii) identifying if hydrogen consumption processes are measurable in a borehole and; iii) evaluating the role of microbial activity on these processes. The experiment involves circulation of gas in an ascending borehole. H_2 along with two noble gases, He and Ne, has been continuously added to the circulating gas over more than 500 days between 2011 and 2013. H_2 concentration has been monitored by online measurement and gas sample analyses. Consumption of H_2 has been demonstrated relative to He and Ne, which were introduced as conservative tracers (Vinsot et al. 2014). Plans for 2016 include continued injection and monitoring of the gas, seepage water composition and microbial activity, as well as further interpretation and modelling to further delineate consumption processes for H_2 in situ.

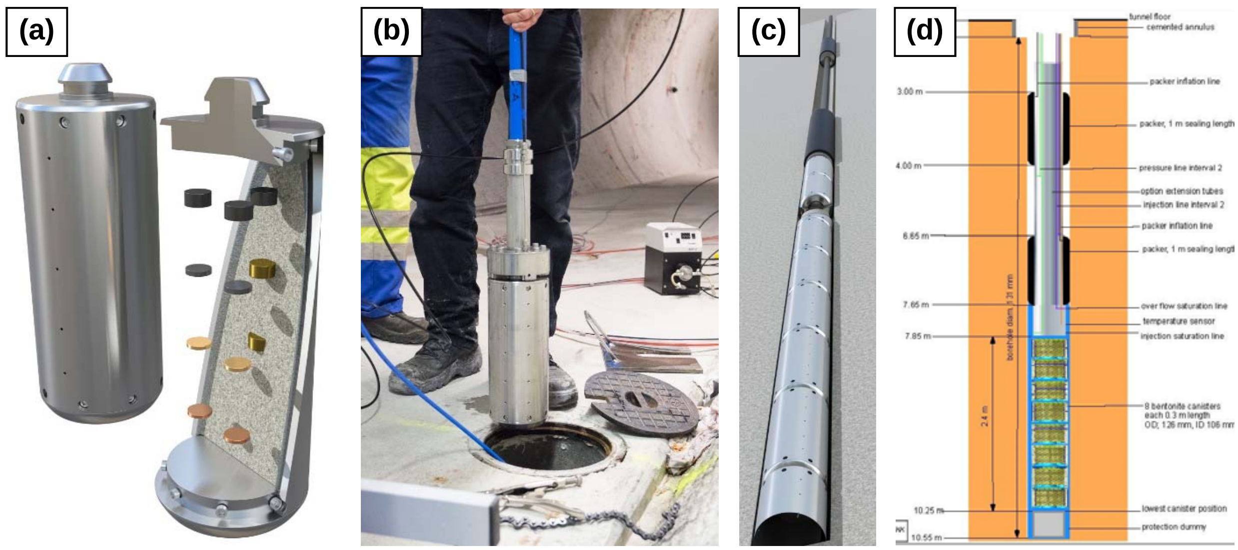


Figure 3.29: Materials Corrosion Test at the Grimsel Underground Research Laboratory Illustrating (a) Copper and Steel Corrosion Coupons in Bentonite (b) Insertion/removal of Borehole Module and Series of Modules Within the Borehole as (c) Cartoon and (d) Schematic Showing Depths and Packers

NWMO-sponsored laboratory experiments at the University of Saskatchewan continued to demonstrate that microbial growth is inhibited in highly compacted bentonite. Results from previous short-duration (40-90 days) studies with highly-compacted Wyoming MX-80 bentonite revealed that a uniform dry density $\geq$1.6 g/cm^3 (with swelling pressure above 2 MPa), water activity below 0.96 and an average pore size of < 0.02 µm, suppressed microbial growth. In 2015, results from a long-term (7-year 264-day) experiment with a high-density clay supported by NWMO were published (Jalique et al. 2016). Results from the analysis of the clay plug were then compared to the earlier short-duration experiment results. It was determined that previous conclusions were accurate, and that the number of readily culturable cells in the clay plug incubated for ~8 years approximated the background numbers originally present in the as-purchased bentonite clay. Bacterial isolates recovered from the clay plug were identified using the Biolog™ GEN III system and 16S rRNA gene sequencing, with both methods revealing only the presence of Gram-positive spore-forming and non-spore forming bacterial isolates. Gram-positive microorganisms have the tendency to survive in these highly-compacted bentonite environments because they are relatively inactive or exist as spores.

Highly compacted bentonite clay is a challenging microbial habitat and microbial activity is expected to be extremely slow. Traditional microbiological methods measuring activity are difficult to apply, and new, simple, accessible tools were developed by Ryerson University to evaluate microbial ecology and metabolic processes in bentonite (Stone et al. 2016). Tools optimized for assessing localised microbial activity within bentonite included: (a) the qualitative use of the resazurin-resofurin indicator system for redox localization, (b) the use of a $CaCl_2$ buffer for the localization of pH, and (c) fluorometry for the localisation of precipitated sulphide. The use of the Carbon Dioxide Evolution Monitoring System was also validated for measuring microbial activity in desiccated and saturated bentonite. These tools will be applied to experiments evaluating the potential for microbial activity at the edges of bentonite blocks.

In 2015, the modelling work program with York University continued to develop a 3D numerical model to evaluate diffusion of sulphide through bentonite and microbiologically influenced corrosion (MIC) of the used fuel canisters (UFC). The model was developed using COMSOL Multiphysics, a finite element software package. COMSOL is a commercial 3D simulator that is capable of parametric design (allowing for quick changes to the model geometry). In the absence of site specific sulphide concentrations, the model conservatively assumed a constant flux of 3 ppm sulphide at the host rock interface. Validation of the software package was conducted against analytical solutions of diffusion in 1D, 2D and for cylindrical and spherical shells in 3D. The model showed that with a constant concentration boundary condition applied at the host rock and at the UFC surface, the sulphide flux driven through the Engineered Barrier System (EBS) was the highest at the semi-spherical end caps (Figure 3.30). This demonstrates the importance of 3D modelling, highlighting the non-linear diffusion through semi-spherical surfaces. Corrosion from MIC will be site-specific, as it is dependent on the hydrogen sulphide concentration in host rock porewater that diffuses through the buffer to the container. Future work will continue to develop 3D models.

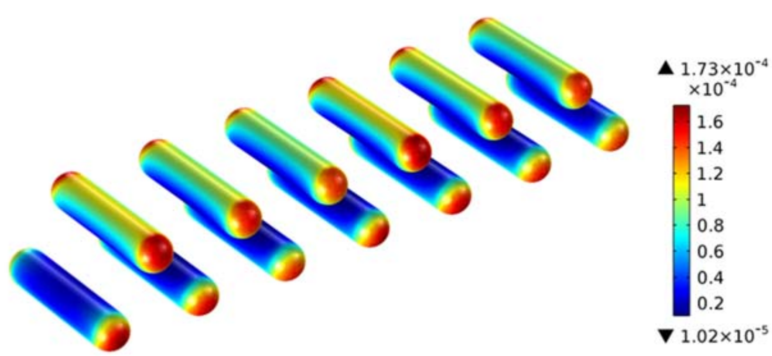


Figure 3.30: Flux of Sulphide in mol/m^2/year at the Container Surface Using a Generic Concentration of 3 ppm Sulphide at the Host Rock-bentonite Interface

3.4 SITE AND REPOSITORY

The NWMO continued to support the development of layout concepts for the Mark II Used Fuel Containers in both crystalline and sedimentary rock. In 2015, a numerical modelling exercise was carried out to assess the optimized Mark II placement room design as shown in Figure 3.31. Design enhancements to simplify operations and reflect more realistic analysis assumptions were proposed and include:

- A thin concrete driving surface for improved driveability during placement;
- Elimination of stacked buffer box offset;
- Replacement of floor gap fill with highly compacted bentonite tablets;
- Fabrication of the spacer blocks from Highly Compacted Bentonite, and
- Elimination of unrealistically conservative assumptions in thermal modelling that assumes the saturation of the buffer is 0 %, instead of assuming the moisture within the buffer is redistributed from the as-placed condition.

The spacer block thickness was varied to determine the thickness which resulted in a UFC maximum temperature of less than 100 °C. Based on the analysis carried out, it was determined that the spacer block thickness is 700 mm for the sedimentary geosphere and 300 mm for the crystalline geosphere for a room spacing of 25 m.

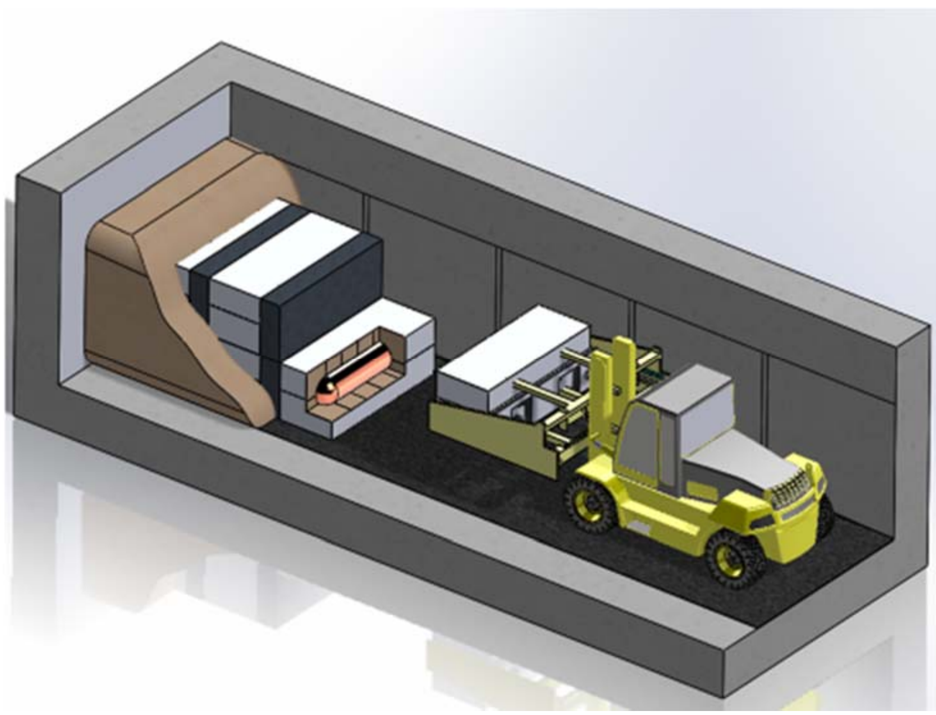


Figure 3.31: Illustration of Revised Concept Showing Direct Stacking of Buffer Box

4. GEOSCIENCE

In collaboration with experts, both in Canada and internationally, the NWMO is pursuing an active technical program, which addresses a wide range of topics related to the development of DGRs for used nuclear fuel. The primary objectives of the NWMO's geoscience technical program are to: 1) ensure preparedness to conduct site characterization activities for the purpose of evaluating the adequacy of potential candidate sites in both sedimentary and crystalline environments for a deep geological repository; 2) advance understanding of the geosphere in terms of stability, predictability, and resilience to long-term perturbations; 3) substantiate the role of geoscience in establishing support for a DGR safety case; and 4) maintain a high level of competency and a credible Canadian-based technical program, by involving both national and international specialists and universities in the development of the geoscience approach for evaluating and interpreting geosphere properties, groundwater system behaviour and predictions of long-term geosphere and DGR performance.

4.1 GEOSCIENTIFIC SITE CHARACTERIZATION – LOCAL-SCALE

4.1.1 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. Empirical evidence from underground excavations (Martin 1997), numerical back-analysis (Diederichs 2007) and laboratory testing (Schmidtke and Lajtai 1985) suggest that the lower-bound-rock-strength limit, or long-term strength of rock, should be the crack initiation (CI) threshold. The largest dataset available in the literature on laboratory testing of time to failure during static fatigue tests is from the Lac du Bonnet granite (at the former Whiteshell Underground Research Laboratory in Pinawa), 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). This was verified by a limited number of long-term strength degradation tests carried out on Cobourg limestone samples as part of the L&ILW Deep Geological Repository site characterization investigation at the Bruce nuclear site (NWMO 2011).

The current testing program aims to verify the argument that the CI threshold is the lower bound strength for limestone. Testing began on the Jura limestone from Switzerland to ensure the testing procedure and sensor measurements would yield the desired output. The time-to-failure for the Jura limestone samples match very closely to the Lac du Bonnet test results (see Figure 4.1). Cobourg static fatigue testing has been conducted on 5 samples to date and the preliminary results also indicate a similar trend to the Lac du Bonnet granite and Jura limestone test results. Static fatigue testing of the Cobourg will continue in 2016.

Relaxation testing represents the opposite test control parameter, i.e., constant strain instead of constant stress. Tests were conducted on both the Jura and Cobourg. The results indicate that the maximum stress relaxation (stress drop with time) occurs at higher load thresholds. The maximum relaxation was 7.4 MPa and 16.2 MPa for the Jura and Cobourg, respectively. At load thresholds near or below CI the stress relaxation reaches a minimum value. The results suggest that increased stresses in the rock mass, elevated as a result of construction activities can reduce with time post-construction.

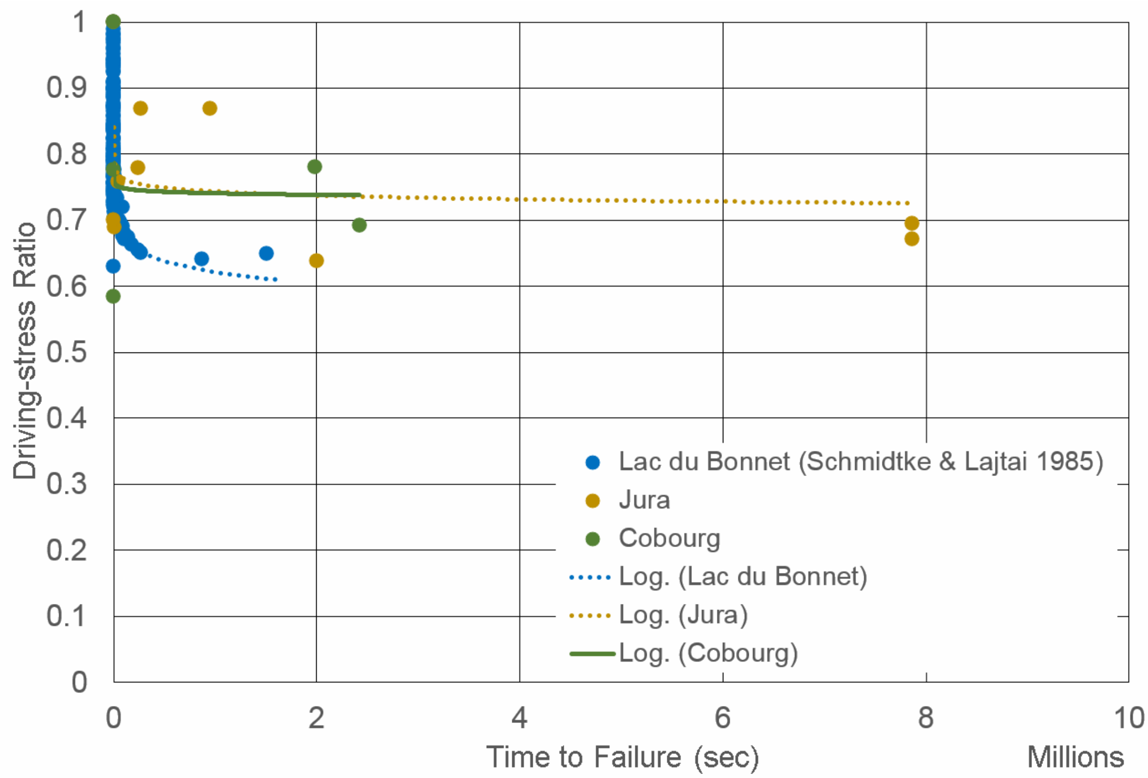


Figure 4.1: Comparison of Time-to-Failure Results from Static Fatigue Testing on the Lac du Bonnet Granite, the Jura Limestone and the Cobourg Limestone

4.1.2 EDZ Cut-off Configuration Assessment

A key aspect in the design of a used fuel repository is the long-term performance of repository seals or cut-offs. The concept of constructing a cut-off by means of excavating slots or keys perpendicular to the axes of the excavated repository opening, and filling these cut-off structures with bentonite-based material or concrete, has been investigated numerically in this research program initiated in 2014. The seals are required to cut-off the potential exposure pathways along the Excavation Damage Zone (EDZ).

Empirical evidence, from EDZ depth investigations for nuclear waste repository design suggests that, in many rock types, the damage process is of a brittle nature (Perras and Diederichs 2016). In the current study, brittle material behaviour has been implemented in numerical models representative of various rock types and stress scenarios. Both circular and square openings have been modelled with three different cut-off shapes, including thin-slot, triangular, and trapezoidal of various dimensions, to establish a cut-off dimension selection criteria. In order to assess the cut-offs effectiveness in intersecting the EDZ, the methodology of NWMO (2011) and Perras and Diederichs (2016), which utilizes the volumetric strain as an indicator of the transition from contraction to extension, has been followed. Using this concept, the performance of the cut-off seal at intersecting and minimizing the expansion of the inner EDZ will be assessed. In Figure 4.2 a triangular cut-off is used to illustrate the minimal zone of inner EDZ expansion at the tip of the cut-off seal.

This numerical modelling investigation will provide preliminary information on dimensioning of cut-off excavations that can be used in supporting reference-engineering designs and illustrative safety cases. The study is intended to explore a broad range of possible geologic settings using a systematic continuum-based modelling approach.

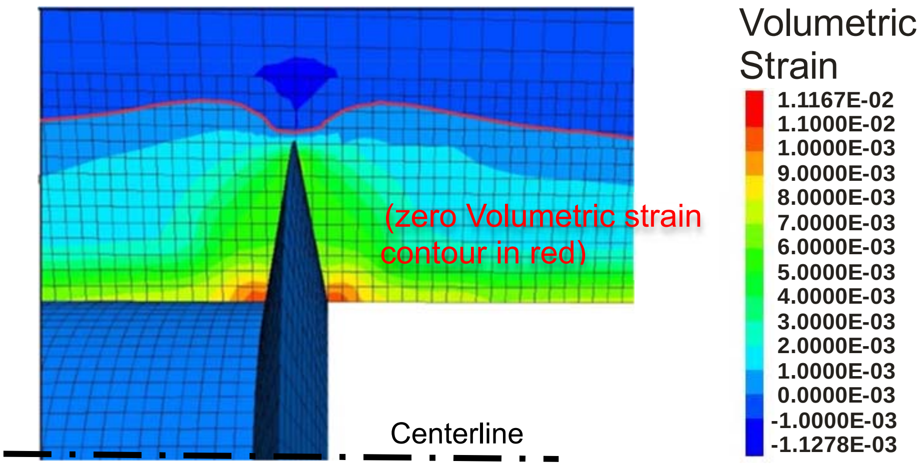


Figure 4.2: Contours of volumetric strain around a triangular cut-off seal (T/D ratio of 1:3). The transition from extension (inner EDZ) to contract (outer EDZ) is indicated by the red line.

4.1.3 Long-term Stability Analysis of Mark II Repositories

A numerical study was completed in 2015 to provide a quantitative 2D and 3D assessment of the long-term geomechanical stability of near- and far-field rock mass-barrier integrity, enclosing a Mark II conceptual used-fuel DGR, on timeframes commensurate with DGR safety (i.e., 1 Ma). The analyses were intent on exploring the repository configuration and designs in both crystalline and sedimentary settings. A focus was placed on providing a reasoned and quantitative understanding of near- and far-field rock mass response to stress redistribution created by long-term geologic, climatic and repository-induced perturbations. In particular, the impact of low probability earthquakes, glaciation, thermal effects from the decay of waste, and gas generation within the repository were examined. The results can be used to provide an illustrative simulation to convey knowledge with respect to the robustness and passive safety of the APM repository concept. The project is intended to serve as a quantitative basis to evaluate the long-term integrity of natural barriers, as well as far-field impacts that could influence the engineered design – consistent with the development of a strong safety case.

In the sedimentary rock scenario, the repository is considered to be excavated within the Ordovician Cobourg Formation, an argillaceous limestone of approximately 45 m thickness within a sedimentary sequence of shales and carbonates. The floor of the placement rooms has an invert level at a nominal depth of 500 m below ground surface. The limestone is overlain by more than 230 m of Upper Ordovician shale-dominated cap-rock. For the crystalline case, the repository will be excavated at the same nominal depth but in a low-permeability granitic rock mass.

Based on the analyses of both scenarios, rock mass damage in close proximity to the excavated repository openings occurs as a result of: in situ stress magnitude and orientation, thermally-induced stress changes, and time-dependent rock mass-strength degradation. The damage evolves with time but is primarily driven by thermally-induced stress changes. Maximum thermally-induced stress changes and rock mass damage occur before 2,000 years. The rock damage is predicted to be approximately 1 m around placement rooms. If bedding planes exist in the limestone host rock, slipping and micro-cracking might occur within 2 m from placement rooms. In a crystalline setting, randomly distributed cracking could extend 3 m into the granitic rock mass. Figure 4.3 shows the stress state and damage in host rock around a placement room up to 50,000 years in a sedimentary setting.

In addition to the above analysis, the effects of rare and extreme seismic ground motions and glacial loading (typical of the Laurentide Ice Sheet) are small, with results revealing virtually no increase in rock mass damage. Bounding simulations that considered extreme combinations of loading (e.g., rare seismic ground motions at maximum far-field temperature and glacial ice sheet loading) also indicate virtually no increase in rock mass damage (Figure 4.4). It is evident that the engineered backfill system provides the necessary confinement to prevent spalling and/or fracture dilation, and likely contributes to slowing the rate of time-dependent strength degradation.

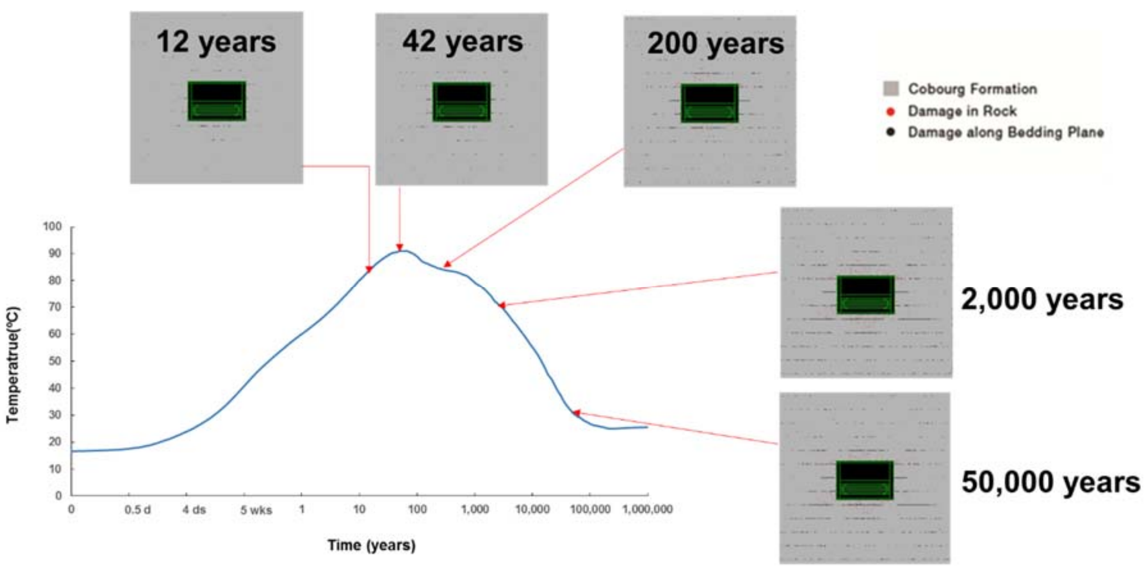


Figure 4.3: Evolution of Damage in Sedimentary Rock

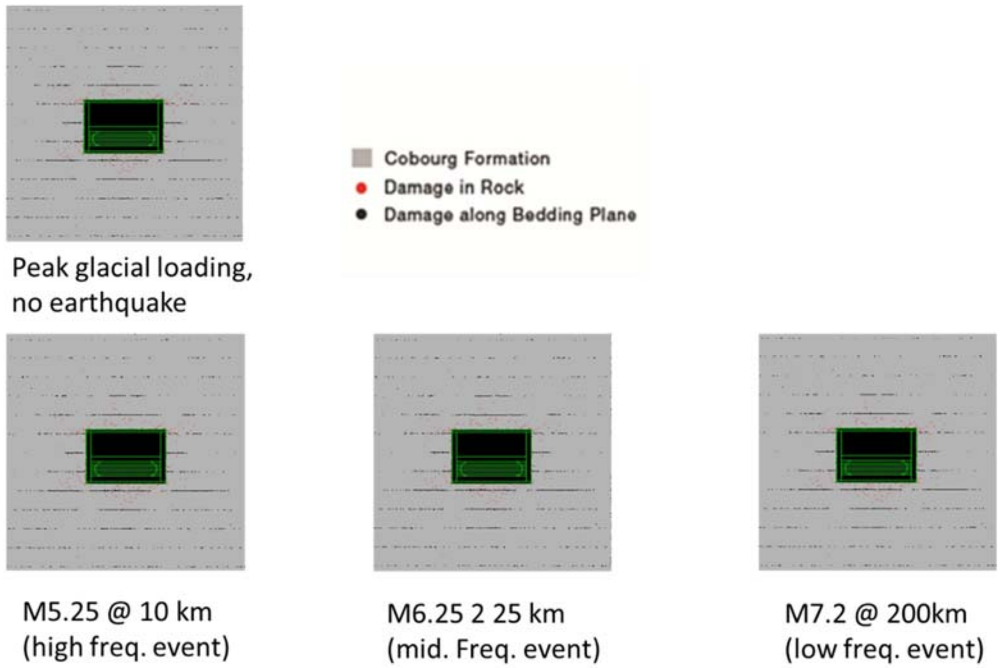


Figure 4.4: Microcracks in the Rock at Peak Glacial Load Subjected to Three Different Earthquakes at 10^{-6} p.a. Probability Level in Sedimentary Rock

4.1.4 Synthetic Rock Mass

The Synthetic Rock Mass (SRM) research program brings together researchers at the University of Alberta and Queen's University. This research aims to advance our numerical modelling approach in the prediction of the response of rock masses to the applied mechanical, thermo-mechanical, hydro-mechanical, and other types of loading, in order to facilitate the design and excavation of a DGR in both crystalline and sedimentary rock. The requirements to forecast the response of the rock mass containing a repository far exceed the traditional design expectations for underground civil or mining projects. Consequently, there is a significant reliance on numerical modelling and prediction. This research will advance the numerical modelling approach, utilizing the concepts embedded in the synthetic rock mass, and will demonstrate the validity of the approach utilizing the results from laboratory and field testing programs that have been carried out by the NWMO and collaborators over the past 10 years.

The outcomes from this work will: (i) advance current understanding of rock mass strength, (ii) develop methodologies for assessing strength based on Discrete Fracture Networks (DFN) and scale effects, (iii) develop methodologies for assessing rock mass behaviour subjected to coupled processes, and (iv) develop numerical tools that can be used during the design, construction and performance evaluation of a DGR.

The SRM research is a multi-year work program and is a co-funded project with the Swedish Nuclear Fuel and Waste Management Company (SKB), for which the main interest is using SRM applications in crystalline rock. NWMO extends the research to develop this modelling method for applications in sedimentary rock as well, particularly for limestones and shales. The work can be divided into the following fundamental areas: (i) grain-based (micro) modelling (GBM), (ii) sample/block (meso) scale modelling of intact rock, and (iii) larger/excavation (macro) scale modelling with joint and bedding systems. Figure 4.5 shows the transition from grain based models to discrete fracture networks. The building stone for the SRM is the discrete element model (DEM) formulation using bonded particles (2D or 3D spheres or Voronoi discretization) and DFN generation software ranging from purely stochastic to primarily genetic algorithms.

The research at Queen's University has been focusing primarily, although not exclusively, on sedimentary rock environments and uses the optimization of synthetic rock mass techniques for geomechanical analysis. The program of SRM modelling takes a novel approach in comparison to the traditional continuum and discontinuum methods to simulate the fracture of intact rock and the deformation along existing discrete fractures using Discrete Element logic to capture the failure of the individual components and their interactions. In addition, the complimentary technology of discrete fracture networks is integrated so that realistic clusters of pre-existing discontinuities can be modelled.

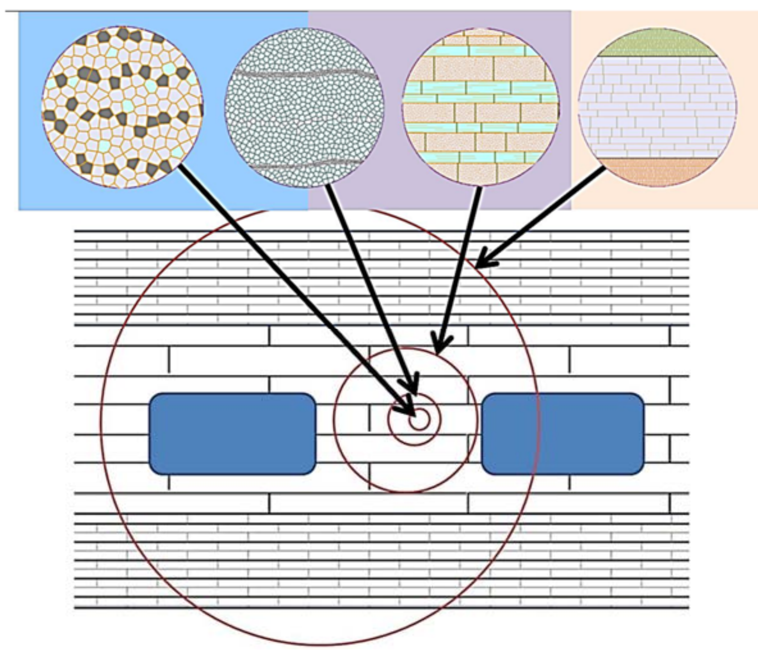


Figure 4.5: An Illustration Showing the Transition From Intact (GBM) to a Bedded-Jointed Rock Mass (DFN) with Increasing Sample Size

4.1.4.1 Discrete Fracture Networks, DFN

A divergent approach to DFN generation has been developed to extract discontinuity and fracture data from 3D rock-mass models using remote sensing techniques, and more specifically LiDAR scanning, in order to derive input parameters for DFN generation (Vazaios et al. 2014a, 2014b). Figure 4.6 shows the geometric modelling of DFNs and their implementation in numerical modelling.

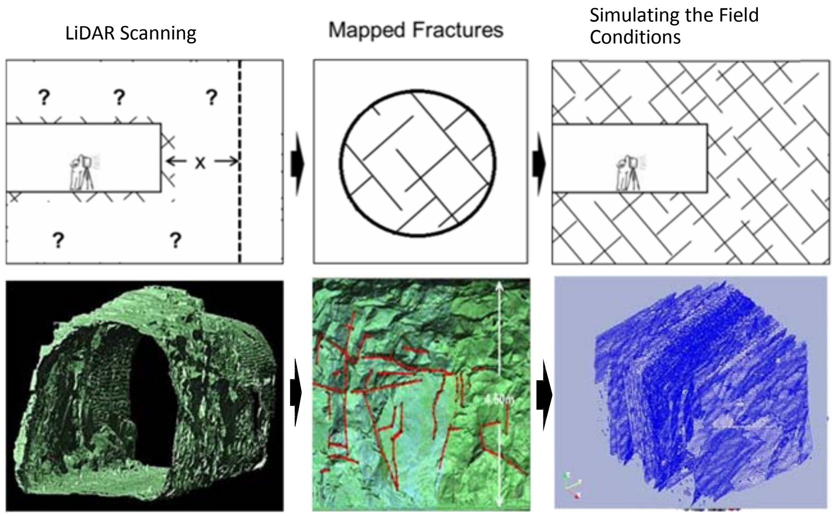


Figure 4.6: Geometric Modelling of DFNs and Their Implementation into SRM Modelling

DFNs generated with MoFrac (see Section 4.2.9) have been used to: i) examine data-collection and fracture-related biases during the sampling process, and its effect on DFN generation; ii) to examine its capability in estimating structural failure mechanisms in underground works; iii) to examine the concept of the Representative Elementary Volume (REV) and its application; and, iv) to examine its capability, based on data availability, to make estimates for the rock mass conditions in places where data is not readily available (i.e., sections of a tunnel ahead of the excavation face), and then to create hybrid DFN-DEM models using MoFrac and UDEC in order to examine the effect of an existent fracture network on the strength of a specimen and how this is affected by the different scales employed.

The importance of accurate and geologically valid DFNs for geomechanical analysis were demonstrated, using geological uncertainty in stability models, to illustrate the impact of geological dissimilar environments on failure mode and stability assessment (van der Pouw Kraan and Diederichs 2014a, 2014b; van der Pouw Kraan et al. 2014). The work demonstrated the failings of conventional rock mass classification systems, and rock mass strength assessment tools, to capture the geological controls on excavation stability.

Further investigations on the impact of input mechanical properties on meso-structure simulated in either finite element or discrete element models using DFN were carried out, with aims to study the impact of filled or incipient discontinuities, such as veins or bedding (Day et al. 2014, 2015). The selection of model vein or bedding mechanical properties were investigated and rationalized. In 2016, laboratory testing is planned - aiming at refining bedding plane or surface properties within the heterogeneous Cobourg Limestone.

4.1.4.2 Grain Based Models, GBM

Ghazvinian et al. (2014) initiated the project described below based on early work related to the synthesis of brittle damage processes within a grain-based PFC model. The influence of various clustering and clumping techniques to simulate inherent dilatancy due to grain interaction were studied and optimized. A Voronoi generation algorithm to create random polyhedral grains within a composite material model was rendered in 3D discrete element models to study the impact of grain size, grain and interface properties within the model, and the impact of anisotropy in sedimentary rock resulting from stress-induced fracture.

A similar approach, using a 2D Discrete Element Model (DEM) to create a hydro-mechanical coupled model, to investigate permeability evolution during grain-scale damage processes active within the EDZ was carried out in 2015 (Farahmand and Diederichs 2015). In 2016, validation testing will be carried out, in addition to further model development.

A similar Voronoi approach, in combination with DFN generated bedding and joint scenarios, was used by Day et al. (2014, 2015) to investigate structural impacts and associations with damage processes, as well as provided a vehicle for simulating damage propagation at a scale of mesoscopic (intrablock) defects within joint-bounded blocks. Heterogeneous rocks, such as the Cobourg Limestone, are suitable for such an approach, which bridges the techniques of equivalent homogeneous rock mass analysis and purely structural DFN simulation. More studies to investigate the challenges of upscaling the grain-based approach to excavation and pillar scale analysis will be carried out in 2016.

4.1.5 POST

POST is a collaborative project between Posiva Oy, SKB (Swedish Nuclear Fuel Waste Management Co) and NWMO. The project was initiated in 2014 and is anticipated to complete its first phase in 2016. The objective of the POST project was to develop a strategy and guidelines for determining the parameters necessary for assessing fracture stability at the deposition tunnel scale for repository design and post closure assessment. The research is primarily aimed at supporting the KBS-3 type of disposal concept. However, the outcome of the research can be adopted for NWMO repository designs.

During this initial phase, the feasibility of conducting tunnel-scale in situ shear tests in the underground facilities at Äspö, Sweden, and ONKALO, Finland was investigated. These in situ shear experiments would be used to support the development of a fracture characterization methodology suitable for numerical analysis using a constant normal stiffness (CNS) boundary condition that is representative of confined fractures at great depths, as well as simulating large shear deformation (50 mm). The 50 mm slip is based on the amount of shear deformation along secondary fractures that may occur during post-glacial seismic events, causing damage to a used fuel canister in a KBS-3 repository (Börgesson 1986).

Model studies concluded that in situ mobilization of fractures in the Äspö underground facility, by building up of ground stresses using the slot drilling technique, would not yield measureable displacements for the experiment (Figure 4.7), and large-scale in situ shear tests would not produce more favourable results/advantages when compared to those conducted in laboratories. Despite these findings, several smaller-scale in situ and laboratory tests were executed during the course of the project. Noticeably, a fracture associated to the BFZ300 fracture system at a depth of 437 m in the ONKALO facility was sheared under a low CNS boundary condition. The test result was back-analysed and provided valuable insight on the influence of fracture characteristics and boundary conditions on its shear strength behaviour. The test and related model simulations concluded that rough fractures increase shear resistance with increasing shear displacement, highlighting the importance of characterizing the geometrical characteristics of the fractures. Figures 4.8 and 4.9 show the setup of the shear experiment and the results of back-analysis.

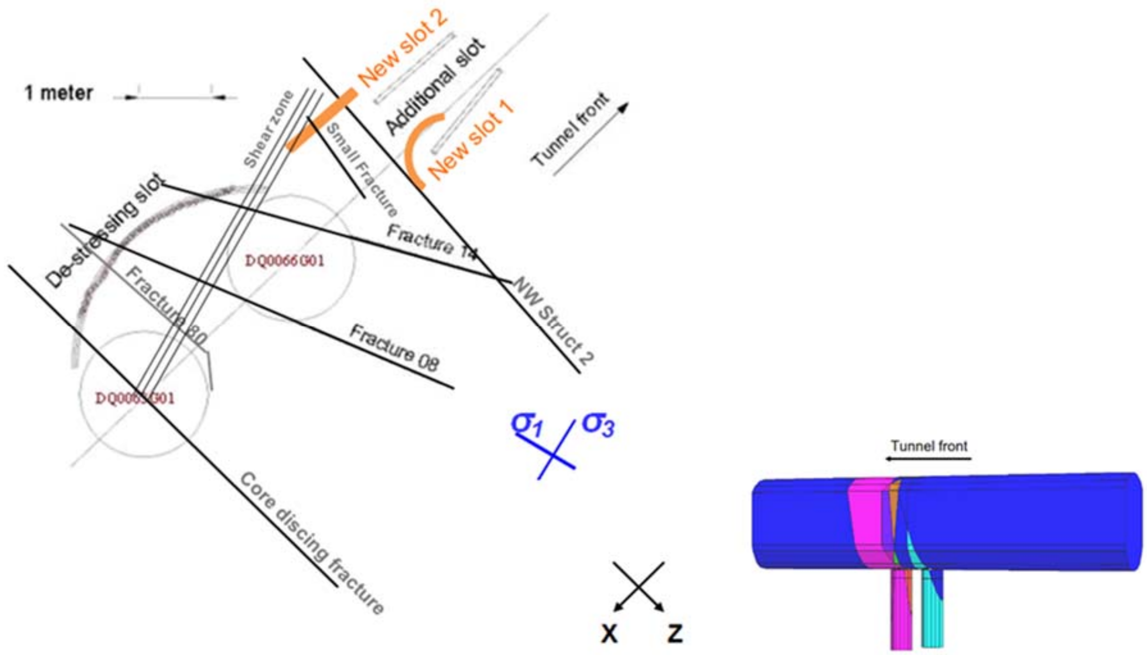


Figure 4.7: Proposed Insitu Shear Test Setup for Äspö TASQ Tunnel Using Slot Drilling to Activate Shear Displacements in a Vertical Fracture (NW structure 2) (Mas Ivars et al. 2015)

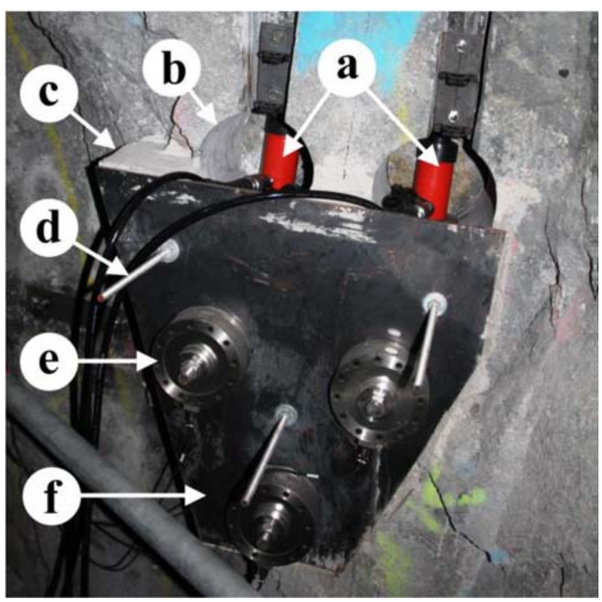


Figure 4.8: In Situ Shear Test Set up on a Fracture Associated with the BFZ300 Structure: a) Hydraulic Jacks, b) Removed Sample, c) Concrete Backfill, d) Attachment Sars, e) Anchor Bolt with Load Cell, f) Steel Loading Plate

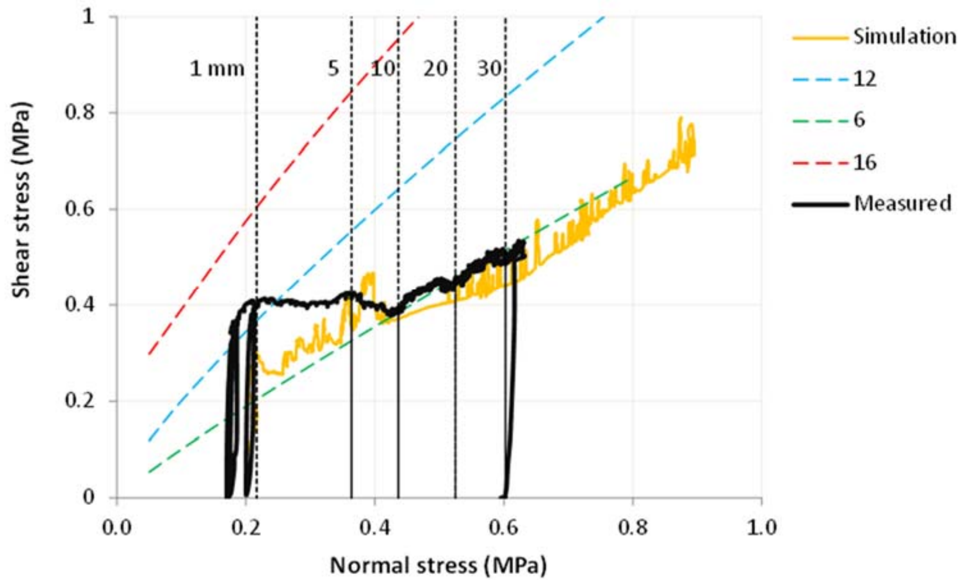


Figure 4.9: Shear vs Normal Stress Plot, with Theoretical Peak Shear Strength Envelopes for Joint Roughness Coefficient (JRC)'s of 6, 12 and 16 Illustrated as Green, Blue and Red Dashed Lines, Respectively. Measured Values are Plotted as a Solid Black Line and the Model Simulation from the Unmated Model in Gold

Because of the challenges with in situ testing, the project focused on the possibility of conducting large scale laboratory direct shear tests using existing facilities in Canada and Europe. However, shear-testing facilities that could generate large normal stresses, as necessary to meet project objectives, could not be located. A conceptual design study for a large direct-shear test device, with a stiff frame sufficient to develop a large normal stress, was undertaken. This device will be constructed, as part of the second phase of the POST project (to be implemented in 2017), to perform well-defined and controlled shear testing on large scale fractures and fracture replica samples in order to examine the shear behaviour of fractures under CNS boundary conditions.

Using the 3DEC numerical code (Itasca 2013), the POST project has also demonstrated that realistic models for the simulation of the behaviour of natural fracture surfaces can be created, based on scanned data of in situ fractures at ONKALO using a 3D photogrammetry technique. Simulations of fully-mated (contact) fractures under CNS boundary conditions reveal an increase in the shear resistance as shear displacement increases. Results show that for 50 mm of shear displacement, the shear stress could reach a magnitude as high as twice that of the initial peak shear stress. The shear resistance was found to be sensitive to the normal stiffness. These findings will be verified by means of shear testing in the next phase of the project.

4.2 SITE CHARACTERIZATION - REGIONAL

4.2.1 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. This program has been ongoing 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.

The seismic activity in the study area during the calendar year 2014 consisted of 36 earthquakes ranging in magnitude from 1.1 m_N to 3.0 m_N. Seventeen earthquakes were larger than m_N 2.0. The largest event, 3.0 m_N, occurred in a remote area of northernmost Ontario on December 3rd. The distribution of the detected earthquakes for this region in 2014 conforms to the pattern of previously observed seismicity (See Figure 4.10). An in-depth discussion of the seismic monitoring results from 2014 are provided in Adams et al. (2015).

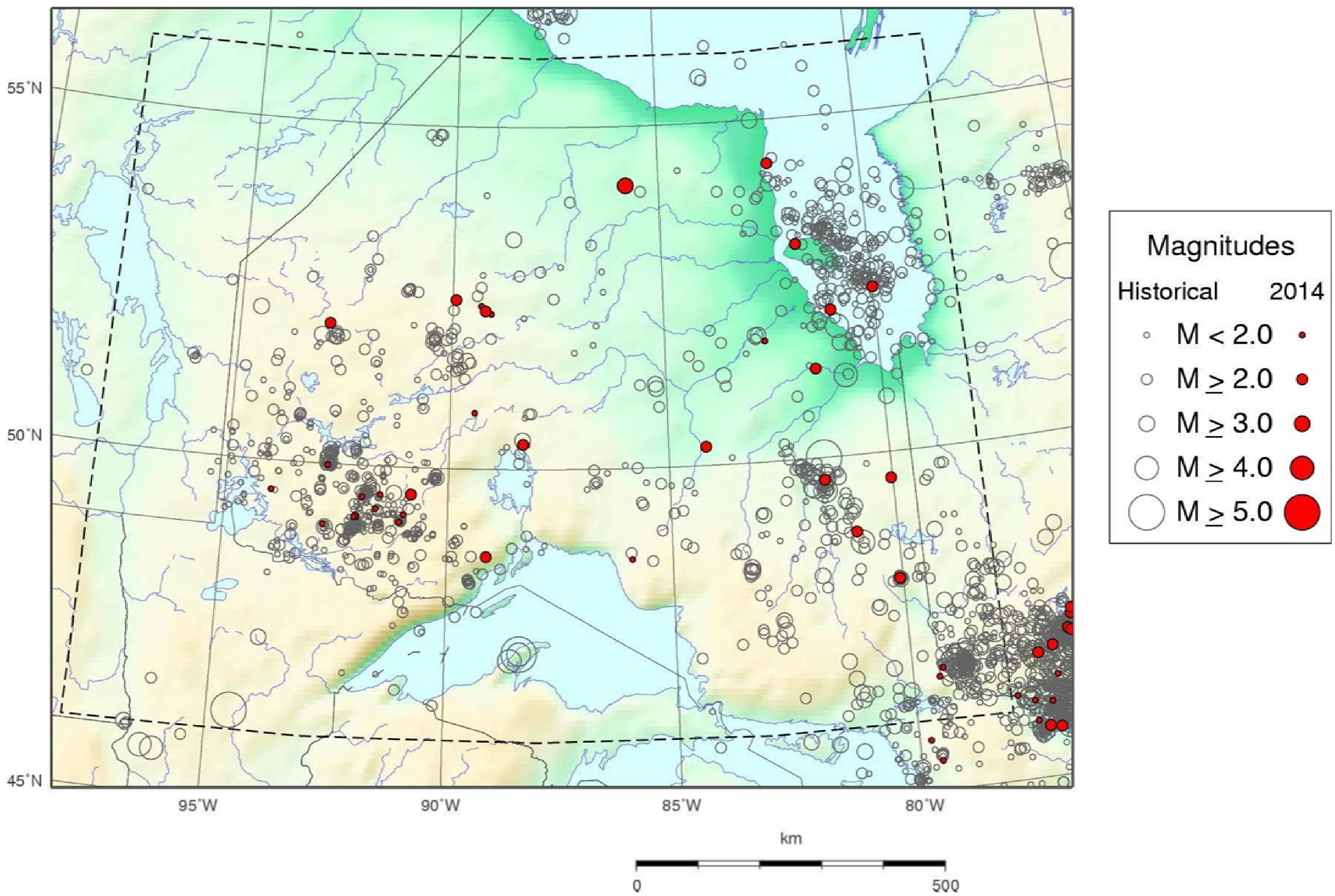


Figure 4.10: Earthquakes in Northern Ontario and Adjacent Areas from 1985 to 2014

4.2.2 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.

Processing of field data collected during 2014 and 2015 has revealed multiple episodic events within the glaciolacustrine deposits in Lac Dasserat, which is situated within the study area. A coring program was completed in 2015 and results were published as a series of open file reports in December 2015, followed by preparation of a paper that will be submitted for publication in January of 2016 (Brooks 2016).

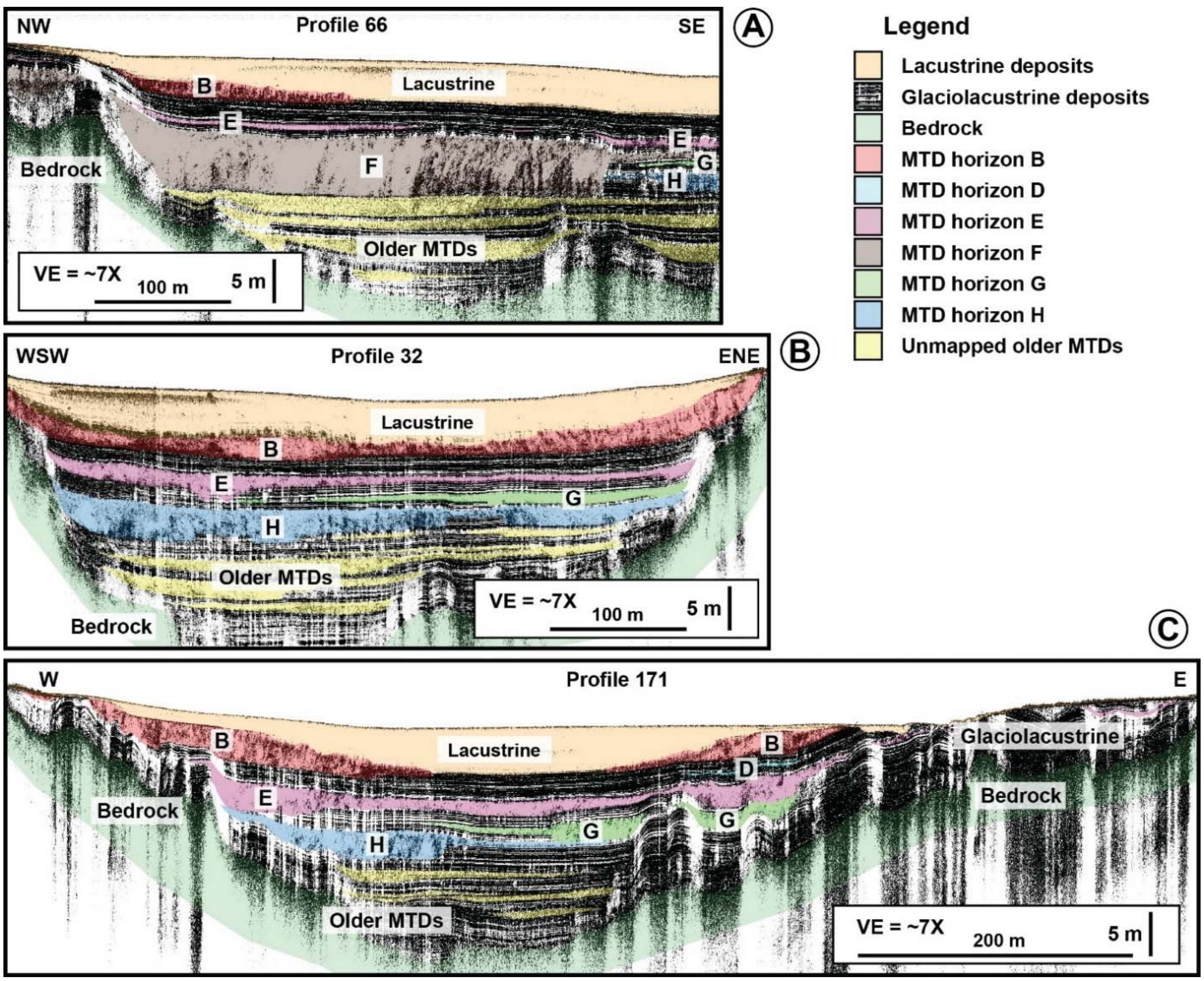


Figure 4.11: Sub Bottom Profiles of Sediments in Lac Dasserat. Six Submarine MTD Deposits Within the Lake Have Been Identified and Labelled

The results of this program show that the integrated seismo- and chrono-stratigraphic investigation at Lac Dasserat, northwestern Quebec, identified 74 separate failures within eight event horizons. Horizons E and B, and H and G (Figure 4.11) have strong or moderately-strong multi-landslide signatures, respectively, composed of 11-23 failures, while horizons F, D, C, and A have minor landslide signatures consisting of a single or pair of deposit(s). Cores collected at six sites recovered glacial Lake Ojibway varve deposits that are interbedded with the event horizons. The correlation of the varves to the regional Timiskaming varve series allowed varve ages, or ranges of varve ages, to be determined for the event horizons. Horizons H, G, E, and B are interpreted to be evidence of paleoearthquakes with differing levels of interpretative confidence, based on the relative strength of the multi-landslide signatures, the correlation to other disturbed deposits of similar age in the region, and the lack or possibility of alternative aseismic mechanisms. The four interpreted paleoearthquakes occurred between 9770 ± 200 and 8470 ± 200 calendar years BP, when glacial Lake Ojibway was impounded behind the Laurentide Ice Sheet during deglaciation. The events likely represent an elevated period of seismicity at deglaciation that was driven by crustal unloading.

4.2.3 Dolomitization: Cambrian and Ordovician Formations in the Huron Domain

A new 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 southwestern Ontario (i.e., Huron Domain). Dolomitization occurs when limestone ($CaCO_3$) is progressively changed to dolomite ($MgCO_3$). Dolomitization can occur by 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. Dolomitization leads to changes in formation density that can alter physical properties of the bedrock, including increased porosity and permeability. In this sense, dolomitization can influence groundwater system evolution through the creation of permeable pathways following lithification and increases the possibility of localized geologic structure suitable for the accumulation of hydrocarbons, a key issue surrounding regional oil and gas resource potential. An understanding of the dolomitization process responsible for the observed conditions within the Black River Group will provide further insight into, and evidence of, fluid movement and temperatures experienced within these formations on geologic timescales.

It is thought that due to the lateral continuity of the sedimentary rock across the Bruce nuclear site that dolomitization there is broadly representative of the Huron Domain region. Previous work in southern Ontario, by the University of Windsor (Haeri-Ardakani et al. 2013a, 2013b), suggested that three dolomite types can be identified in the Ordovician carbonates of the region, based on the integration of petrography, stable isotope, Sr isotope, and rare earth elements (REE) results. In particular, one dolomite type (D3) is uniquely associated with fault-controlled hydrothermal fluids and its identification within sediments can be used to infer the presence of nearby faults.

Results from the Bruce nuclear site were compared to this previous work. Samples were analyzed for their petrographic, isotopic and fluid inclusion composition to assess the dolomitization that represents a wide range of host rocks – including dolomitized limestones (Figure 4.12), dolostones, sandy dolostones and sandstones from the Ordovician Black River Group and Cambrian sequences. The analyses were performed to gain some idea about the nature of the dolomitization of these rocks in terms of their mineralogy, stable isotope composition, fluid inclusions and Sr-isotopic ratios. The petrographic and geochemical attributes provided insight about the fluids that modified these rocks, as well as the possible timing of formation.

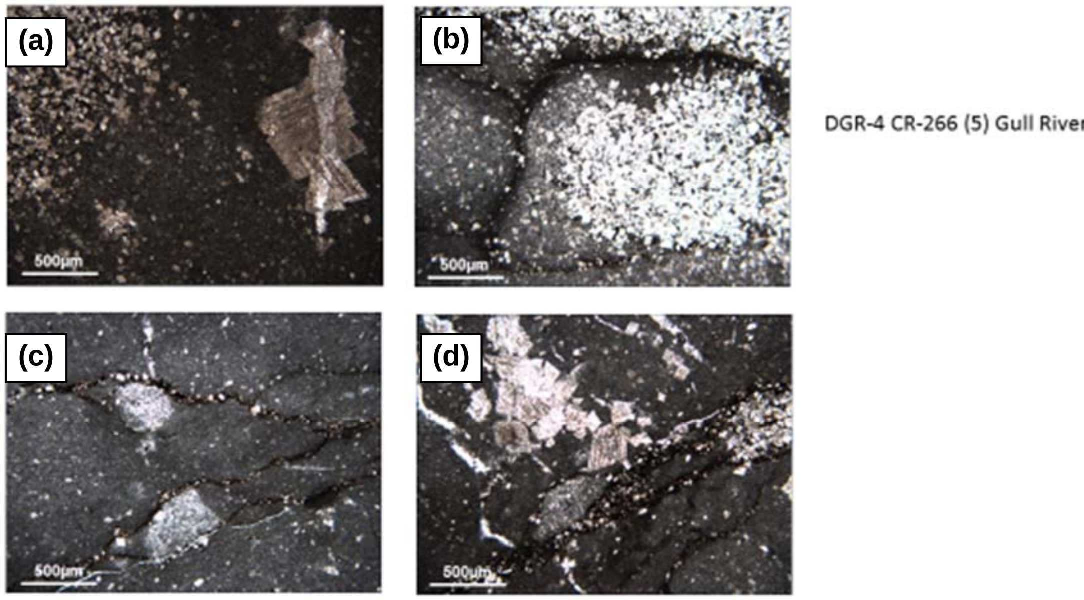


Figure 4.12: Petrographic Features of the Gull River Formation. (a) PPL of the Inter-nodule Matrix and the Intra-nodule Fine Crystalline Dolomite. Note Also the Coarse Dolomite Filling Fracture. (b) PPL of Medium Crystalline, Euhedral Intra-nodule Dolomite. (c) Nodular Facies with Micritic Matrix Cut with Stylolites (black fractures). (d) Selective Dolomitization in the Matrix and Associated with Stylolites

Temperatures in the dolomites range from 66°C to 153°C with the majority of dolomites sampled being of a fine-grained type. Saddle dolomite (D3), commonly associated with faulting, was not identified in the samples provided. Preliminary results indicate an earlier Cambrian system that is characterized by a radiogenic, cooler and saline fluid flow, and a later Ordovician fluid system that is characterized as more saline, more hydrothermal and less radiogenic than the first. The results have shown that some homogenization temperatures were higher than those of the estimated burial depths, indicating the presence of hydrothermal fluids that were not a function of burial-related heating. Isotopic and fluid inclusion data point to two possible, and maybe separate, diagenetic fluid systems.

4.2.4 Calcite Fracture Dating

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 would be of benefit to 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 ongoing at the University of Toronto's Jack Slattery Geochronology Laboratory. An important component of the work program involves development of a methodology to extract reliable absolute ages of calcite mineral growth using a comparative analysis of Laser Ablation-Inductively Coupled Mass Spectrometry (LA-ICPMS) and Isotope Dilution-Thermal Ionization Mass Spectrometry (ID-TIMS) techniques. While this work program is 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 (2014-2015) is currently in the review stage. This report summarizes all geochronology results for the Paleozoic section at the Bruce nuclear site (Figure 4.13), 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 2014-2015 report.

In summary, shallow stratigraphic levels (Devonian-Upper Silurian) preserve ca. 110 to near 0 Ma 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).

In addition to this work at the University of Toronto, work on secondary mineralization has been ongoing at the University of Windsor. The focus of this work has been on calcite and dolomite, which occur in small veins within the Upper Ordovician carbonate rocks of the Trenton and Black River groups in southwest Ontario. Their age and source fluid are uncertain, but limited data for uranium-lead (U/Pb) geochronology, and studies of stable oxygen, carbon and Sr isotopes suggest that they may be of early Paleozoic age with a fluid source originating in the underlying Cambrian aquifer. The current research 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.

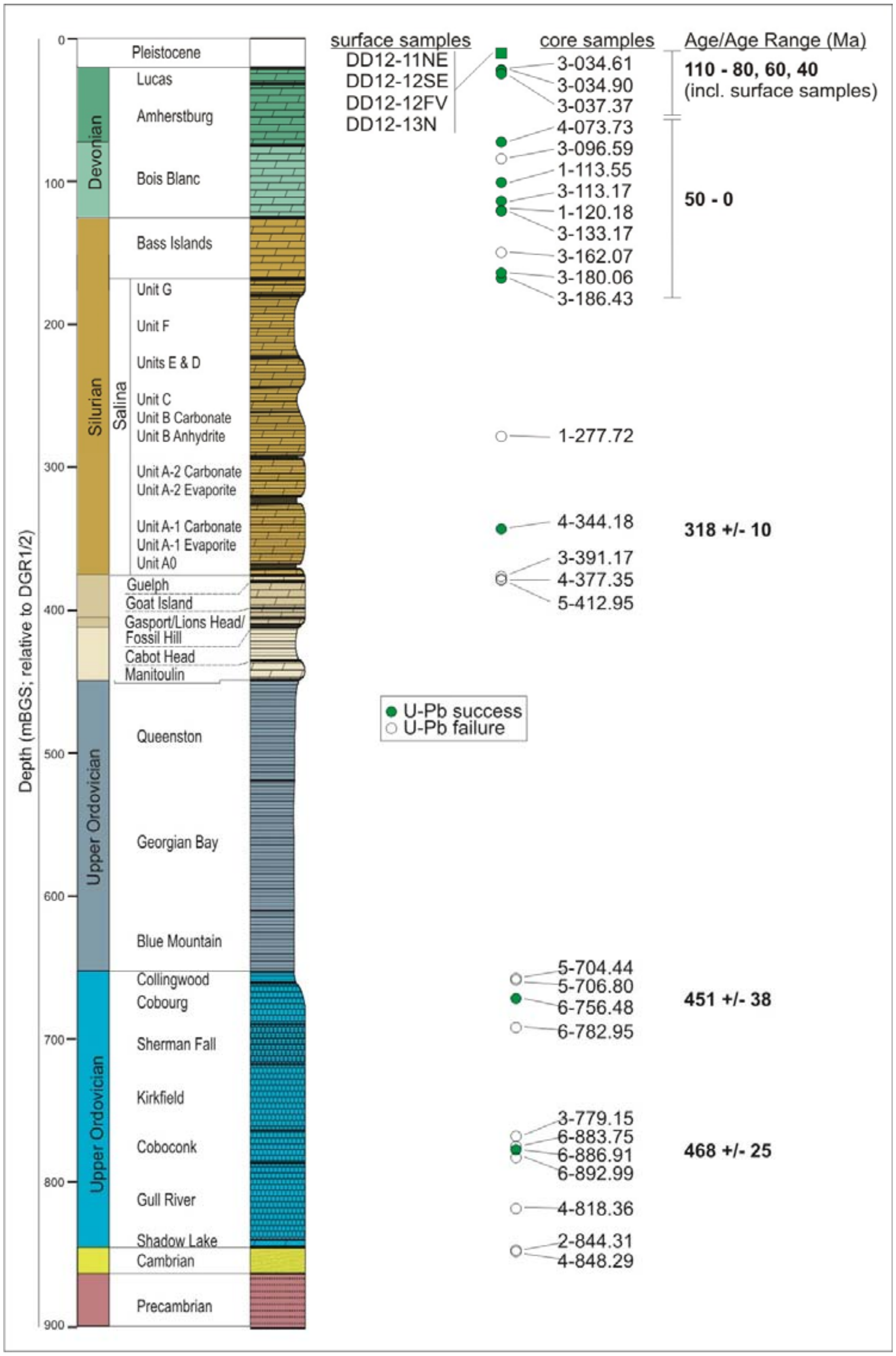


Figure 4.13: Sample Numbers, Locations and Ages Obtained In Relation to the Paleozoic Stratigraphy Beneath the Bruce Nuclear Site for Secondary Calcite Analysed by Davis Between 2013 and 2015. Samples for which U-Pb Geochronology was Successful are Green-Filled and Unsuccessful Samples are White.

4.2.5 Porewater Chemistry and Diffusion Properties

In 2015, 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, as well as to characterize solute transport. The research programs discussed below aim to develop and refine isotopic and geochemical analysis techniques that can be used in site investigation activities in both sedimentary and crystalline rock. Chemical and isotopic compositions of groundwater and matrix porewater, in addition to solute transport parameters (i.e., effective diffusion coefficients), provide information on the origin and evolution of the groundwater system and can be used to determine groundwater fate over geologic time frames. 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.

University of Ottawa

Research undertaken at the University of Ottawa focuses on four main themes: i) solute diffusion; ii) analysis of secondary minerals as indicators of paleofluid properties and movement; iii) characterization of porewater chemical and isotopic composition; and iv) compound-specific isotope analysis of dissolved and solid organic carbon. These research activities are directed toward low-permeability crystalline and sedimentary rocks.

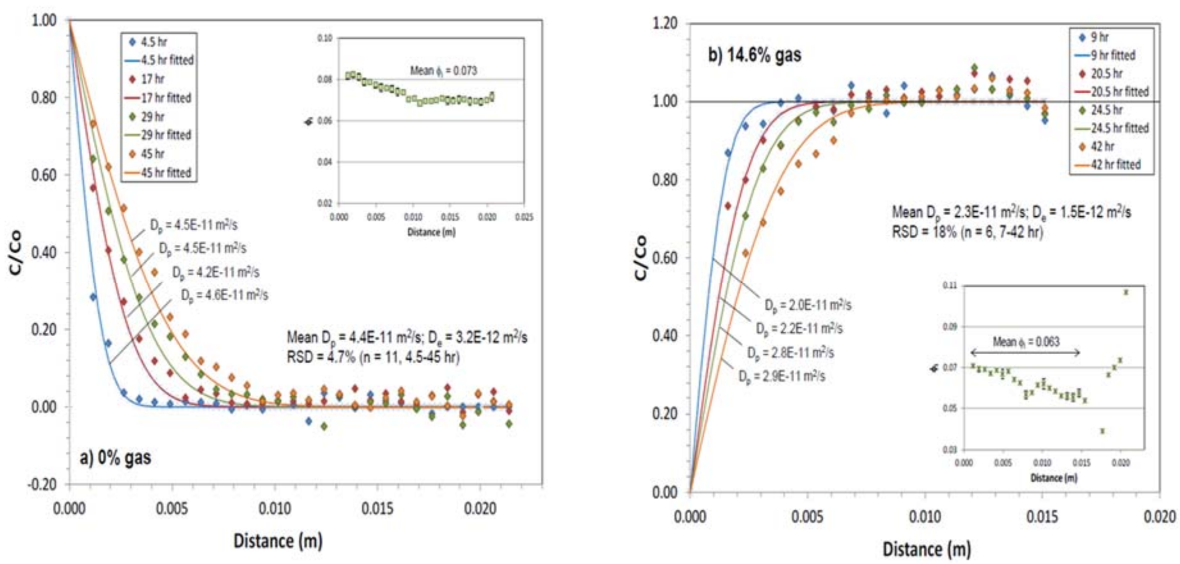


Figure 4.14: Tracer Diffusion Data for a) Fully Brine-saturated and b) Partially Brine-Saturated Samples of Queenston Formation Shale. Note the 53% Decrease in D_e for Iodide that is Observed for Partially Saturated Conditions (14.6% gas, 85.4% brine)

There are two areas of diffusion research: one aims to determine diffusion coefficients for dissolved gases, initially helium (He) and methane (CH_4); the second is intended to quantify the influence of partial brine/gas saturation on diffusion coefficients for aqueous solutes (iodide). In the dissolved gas diffusion experiments, Helium (He) is chosen because it represents a gas that behaves conservatively and therefore provides a benchmark for the highest diffusion rates that might be expected for gases in these rocks. Methane is chosen because it is common in deep sedimentary and crystalline rocks, and a better understanding of the CH_4 transport properties of these rocks is needed to provide additional evidence for the residence time of porewater and gases. In 2015, the experimental design was completed, the apparatus constructed, and analyses were initiated. 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 (Figure 4.14). This research was started at the University of New Brunswick and experience from the previous work led to a re-design of the experimental apparatus for this next phase.

Porewater chemical and isotopic properties are some of the most important data that contribute to a comprehensive understanding of the origin and age, or residence time, of fluids deep in the geosphere. As such, they are critical to understanding the long-term stability of the system. There are a number of methods used internationally to determine these porewater characteristics, all of which are subject to limitations. A novel new method that aims to absorb porewater from the rocks into cellulosic papers has been under development for several years, first at the University of New Brunswick and now continuing at the University of Ottawa. Recent work on this technique has focused on the prevention of artifacts from evaporation during sample processing, as well as improvement of precision and accuracy for the quantification of water content and solute concentrations.

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 due to the presence of clays. A concern that is being examined in the current research is the potential for bias of the vacuum-distillation method due to fractionation between connected-porosity water and clay hydration water. Current research is evaluating this potential effect through a series of experiments involving mechanical extraction of porewater from water-saturated clays, followed by vacuum-distillation. An initial series of high water-to-clay ratio experiments has been undertaken and isotope analyses are pending. A second series with lower water-to-clay ratios will be undertaken in the coming months.

The analysis of porewater isotopes in crystalline rock represents a further challenge that is being addressed in current research. Porewater extraction and analysis from crystalline rocks presents unique difficulties because of the very low porosity (water content) and the common presence of saline fluid inclusions that prevent the use of crush and leach techniques. Thermogravimetric analysis is being evaluated as a first step in understanding the possible reservoirs of water in crystalline rock. The research group has built a high-integrity stainless steel container with conflat copper-and-knife edge seal that can be used to extract porewaters from full HQ (63.5 mm) drill core, and preliminary testing of the equipment has begun.

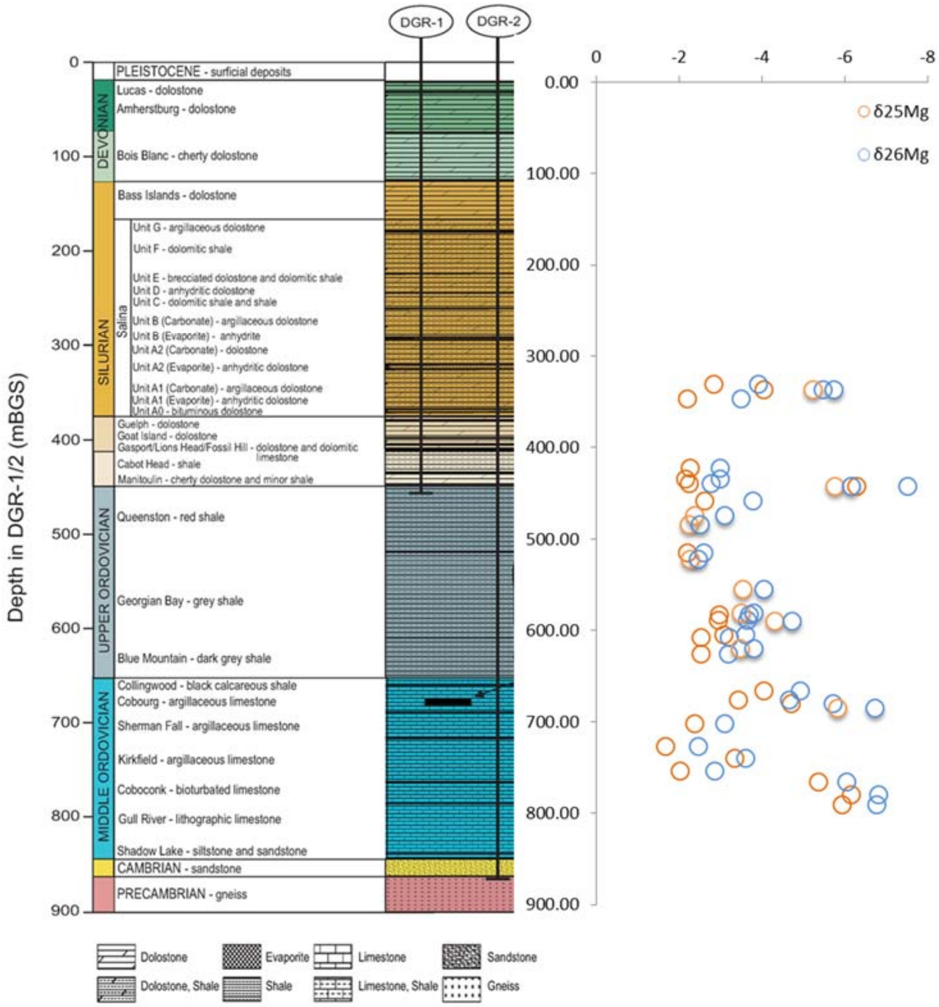


Figure 4.15: Magnesium Isotope Data for the Pore and Groundwater in the Upper Ordovician and Lower Silurian Sediments.

The use of magnesium, calcium and lithium isotopes are being examined in the Bruce profile for insights on the origins of salinity. Magnesium isotopes, in particular, are an emerging tool in the study of dolomite formation, magnesium cycling, and past continental weathering fluxes. The Upper Ordovician carbonate rocks in southwestern Ontario contain post-dolomitic brines that are believed to have residence times exceeding 260 Ma. A current study has generated detailed vertical profiles for the magnesium isotopic compositions of porewaters and groundwaters at the Bruce nuclear site. These data will help to further constrain solute migration and the age of porewaters. Preliminary indications are that the $\delta^{25}Mg$ and $\delta^{26}Mg$ profiles are consistent with a groundwater system that has remained diffusion-dominant over geologic time (Figure 4.15). Current work continues to generate additional detail in the Mg isotope profiles. Lithium concentrations in the Bruce section 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 has been developed. Results are anticipated in 2016, which will be the first such measurements of lithium isotopes for this project. The different potential sources of Li, from evaporated Silurian sea water and from crystalline basement brines, may provide a distinction evident from their $^7Li/^6Li$ ratios.

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 and essentially immobile over time. Volatile fatty acids (VFAs) are key substrates of anaerobic metabolism. Therefore, crucial insights on VFAs sources and sinks can be deciphered from their analysis. As different biogeochemical pathways of production and consumption of VFAs induce different carbon isotopic fractionations, compound-specific isotope analysis (CSIA) on these molecules have the potential to shed light on microbial dynamics in a given environment. Therefore, a sequential leaching method for the VFAs extraction of the different secondary mineral phases is being developed, with the goal of measuring the $\delta^{13}C_{acetate}$ to understand the succession of microbial dynamics in the Ordovician formations. Rock crushing has been carried out at the University of Ottawa in anaerobic conditions to avoid oxidation of dissolved organic matter and sulphide phases. Organic fractions have been carried out with organic solvents and analyzed for composition using facilities at the Delta-lab GSC-Québec. The next steps will be to carry out CSIA. Samples from both the Trenton and the Black River Groups are being processed.

Related isotope research on the Rb-Sr system was completed in 2015, using a sequential leaching protocol to look at the distribution of ^{87}Sr in the carbonate and clay phases with respect to porewaters, with the objective of determining whether enrichments observed in the porewaters are related to ingrowth over time – and therefore representing a new geochronometer for the porewaters at Bruce nuclear site. The excess of radiogenic ^{87}Sr primarily appears to represent ingrowth from ^{87}Rb decay over some 450 million years. Similarly, Rb/Sr errochron ages of carbonate acid leachates, and the apparent initial Sr isotopic ratios, suggest that calcites inherited their Sr from Ordovician sea water and were dolomitized shortly afterward, indicating long-term conservative behaviour of the enclosing carbonate rocks.

<u>University of Bern</u>

Work programs at the University of Bern have focused on: i) porewater characterization; and ii) fluid inclusion chemistry. The work aims to expand the applications/capabilities of techniques (e.g., isotope diffusive exchange, squeezing), which have been applied in various European nuclear waste management programs, to the rock types of most significance to the Canadian nuclear waste management program (i.e., high salinity, low porosity and low permeability sedimentary and crystalline rocks).

In 2015, work continued to develop a benchmarking exercise for both isotope diffusive exchange and squeezing. For isotope diffusive exchange, saturated rock pieces are equilibrated with a test water of known isotopic composition over the vapour phase, from which porewater $\delta^{18}O$ and δ^2H values are derived by mass balance calculations. 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. 2014). Further refinement of the method, in 2015 and on-going in 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. Thus, the next natural step in optimization of the adapted diffusive-exchange technique is to reduce the mass of test water, which is expected to extend the range of applicability of the method to rocks with relatively low water contents (i.e., <2%). The results of this work will be compared with those obtained from porewater squeezing, which was demonstrated in 2013 (Mazurek et al. 2013) to be applicable to Paleozoic rocks of southwestern Ontario. The key objective of the work program 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, pressure solution of carbonates) associated with the high-pressure extraction of porewater.

For the benchmarking work, which is in progress as of December 2015, artificial porewaters of known chemical and isotopic composition are used to saturate rock core samples that are then subjected to squeezing and isotope diffusive exchange. 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 elevated pressures (e.g., 50-500, and possibly up to 750, MPa) from sedimentary rock cores (e.g., shale, limestone) in a confined system, as well as any potential artefacts associated with diffusive exchange.

As noted in Section 4.2.4 a key issue in the long-term safety assessment of a DGR is the need to demonstrate an understanding of the evolution and stability of the groundwater flow system during the period of time for which repository performance must be evaluated. Fluid inclusions trapped within the in-filling minerals of rock cores (veins and vugs) during their growth can provide representative samples of the chemical composition, density and temperature of ancient fluids (i.e., paleofluids). In collaboration with University of Toronto, see Section 4.2.4, a fluid inclusion study at the University of Bern, involving petrographic examination of the vein and vug in-filling mineral phase(s) from selected intervals within Bruce nuclear site cores, was completed in 2015. A final report will be submitted to the NWMO in 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 as well, with research focused on the characterization of vein, vug and fracture calcites found in Silurian-aged rock units from the Bruce nuclear site.

4.2.6 Sorption

Sorption is a potential mechanism for retarding radionuclide transport from a DGR to the environment. NWMO initiated the development of a Canadian sorption database for highly saline groundwaters by conducting a review of the open literature and international sorption databases to find any available data relevant to Canadian sedimentary rocks (shale and limestone) and bentonite clay for the elements of interest for safety assessment (Vilks 2011). This initial database has been augmented with sorption data measured experimentally for elements Cu(II), Ni(II), Pb(II), Eu(III), U(VI), and Zr(IV) onto Canadian sedimentary rocks and bentonite clay in saline solutions using batch sorption tests and long-term diffusion tests (Vilks et al. 2011; Vilks and Miller 2013), as well as any new literature data.

In 2013, a two-year research program in collaboration with Atomic Energy of Canada Limited (now Canadian Nuclear Laboratories) was initiated to further develop the NWMO’s database of sorption coefficient (K_d) values for Canadian sedimentary rocks and bentonite clay for 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, 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 by both batch sorption tests and long-term (1 year) through-diffusion tests; and 2) performing literature review to find any new sorption data for other elements relevant to Canadian sedimentary rocks and bentonite clay in saline conditions.

The research was continued in 2015 in collaboration with Southwest Research Institute to measure the sorption of six key redox-sensitive elements, Se(-II), As(III), Pu(III), U(IV), Tc(IV), and Np(IV), onto Canadian sedimentary rocks and bentonite clay in the highly saline Na-Ca-Cl solution (TDS 275 g/L) under reducing conditions. Kinetic tests were conducted under reducing conditions in controlled atmosphere glove boxes (Figure 4.16) to establish appropriate test durations and initial concentrations of elements in solutions. Two approaches were investigated for performing batch sorption tests in the controlled atmosphere glove boxes: 1) sorption tests were conducted under the required redox and pH conditions of the solutions, within appropriate bounds, for which the elements were reduced to the preferred oxidation states; and 2) sorption tests were started with the preferred oxidation states of the elements achieved using reducing agents. A technical report documenting the sorption measurements in brine under reducing conditions is expected in 2016. NWMO's database of sorption coefficient values for these key redox-sensitive elements will be updated with the experimental sorption coefficient values determined in this research program.

A 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, in highly saline solutions under both oxidizing (as Np(V)) and reducing (as Np(IV)) conditions. The sorption coefficients of Np(V) onto bentonite, shale and illite in highly saline Na-Ca-Cl solutions were measured under oxidizing conditions. It was found that Np(V) was moderately sorbed onto illite and shale, and strongly sorbed onto bentonite in the ionic strength (I) of 0.1 M to 6.0 M Na-Ca-Cl solutions (Nagasaki et al. 2015). The effects of ionic strength, pH, and Na/Ca ratio of the solution on the sorption of Np(V) onto bentonite, shale and illite were systematically investigated in the highly saline Na-Ca-Cl solutions with ionic strength of 0.1-4.6 M. The K_d values on illite and shale were independent of the ionic strength, and the K_d value on bentonite was independent of ionic strength greater than 1.0 M (Figure 4.17a). The K_d values of Np(V) on illite, shale and bentonite increased with pH_c (Figure 4.17b). The research will continue in 2016 to study the sorption of Np(IV) in brines under reducing conditions and investigate the effects of ionic strength, pH, and Na/Ca ratio on the sorption of Np(IV) onto shale, illite and bentonite.

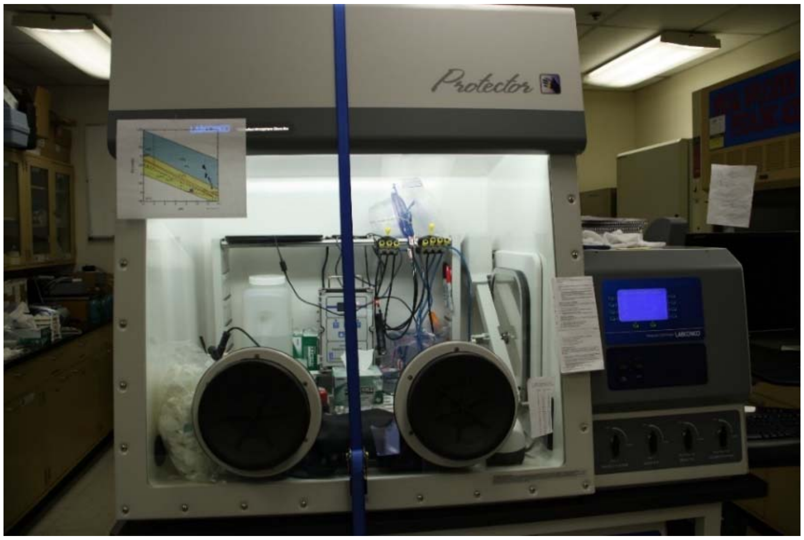


Figure 4.16: Glove Box with Controlled O_2 Concentration (<1.0 ppm) for Sorption Tests Under Reducing Conditions

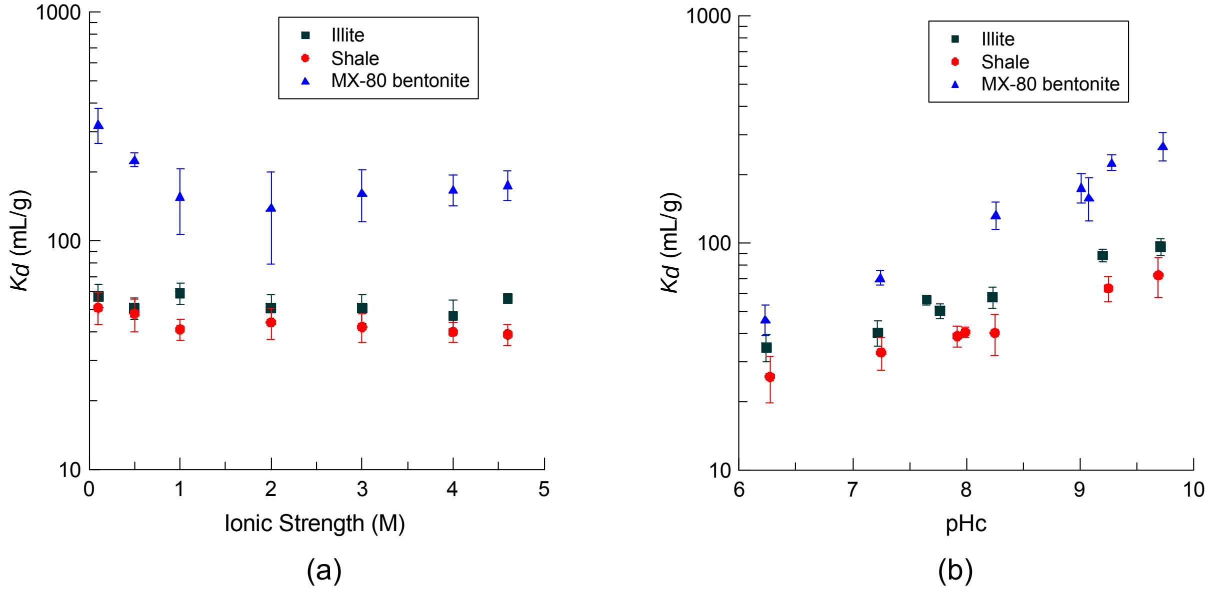


Figure 4.17: (a) Ionic Strength Dependence of Np(V) K_d Values in Highly Saline Na-Ca-Cl Solutions; and (b) pH_c Dependence of Np(V) K_d Values in the Na-Ca-Cl (I = 4.6 M) Brine. The Initial Concentration of Np(V) was $1.0×10^{-5}$ M

4.2.7 ANPOR

The Anion Accessibility in Low Porosity Argillaceous Rocks (ANPOR) research program was initiated in February, 2014 and is jointly funded by the Paul Scherrer Institute (PSI) in Switzerland and the NWMO. It investigates the anion exclusion effect in clay rocks on

Canadian (Queenston and Blue Mountain) and Swiss (Opalinus Clay and Helvetic Marl) samples.

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. All diffusion experiments were performed perpendicular to the bedding plane of the samples (Figure 4.18).

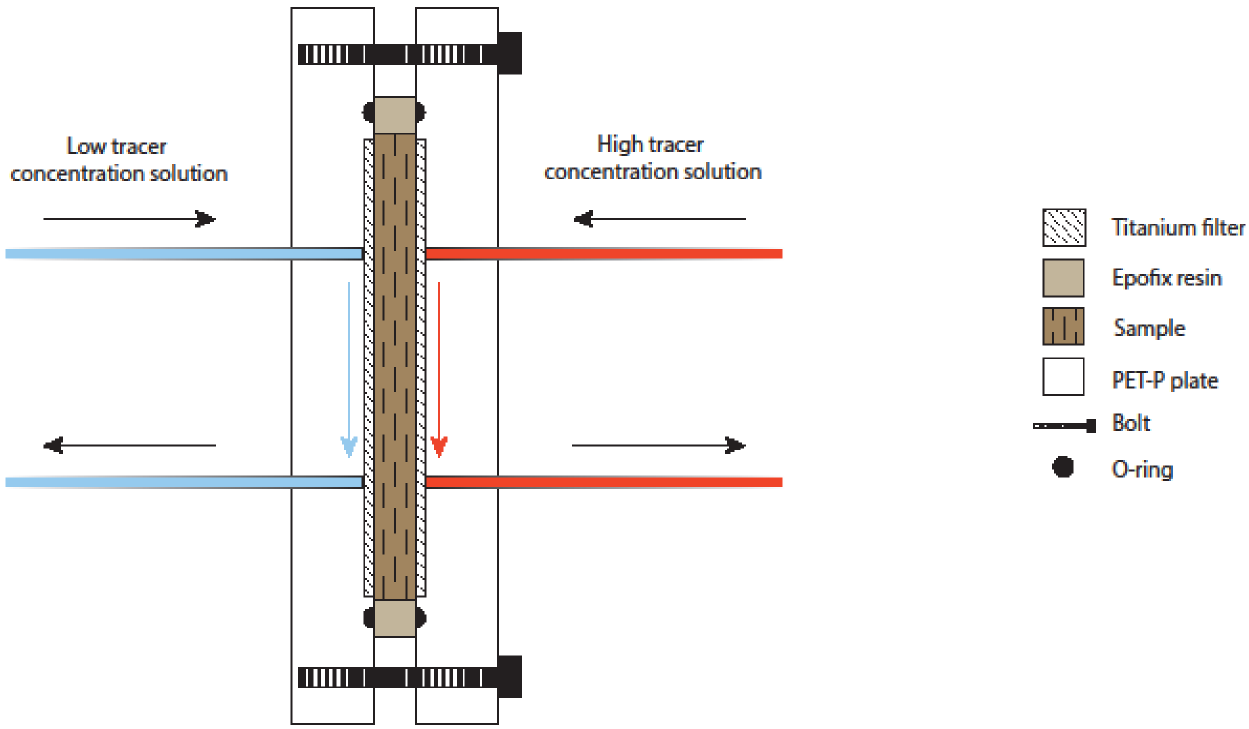


Figure 4.18: Cross-Section View of the Diffusion Cell. The Diffusion Cell Comprised Two Plates Consisting Of Ertalyte®, An Unreinforced Polyester Based on Polyethylene Terephthalate (PET-P). Titanium Filters were Implemented in the Plates (Diameter = 0.065m; Thickness = 0.0012m; Pore Diameter = 1x10^{-5}m). The Solution in the Low Tracer Concentration Container is Replaced Regularly to Maintain the Concentration Gradient Driving Diffusion (Wigger et al. 2016)

The results of the Opalinus Clay (OPA) and Helvetic Marl (HM) samples are illustrated in Figure 4.19a. The through-diffusion of HTO and $^{36}Cl^{-}$ was studied as a function of the ionic strength. The total porosity determined by HTO-diffusion is independent of the ionic strength. OPA has a value of 12% and the total porosity of HM is 3%. The anion exclusion effect in HM is higher than in OPA. Moreover, there is a significant difference in the dependency of the anion accessible porosity on ionic strength between the two clay rocks. One reason is the difference in the mineralogy, wherein HM contains more charged minerals than OPA. Therefore, the repulsion of the anions in HM is more pronounced than in OPA. A more detailed analysis of these results is described in Wigger et al. (2016).

The results of the anion diffusion through the Blue Mountain samples are plotted in Figure 4.19b. The interim results show that, relative to the total concentration, more anions diffuse through the samples at higher ionic strength.

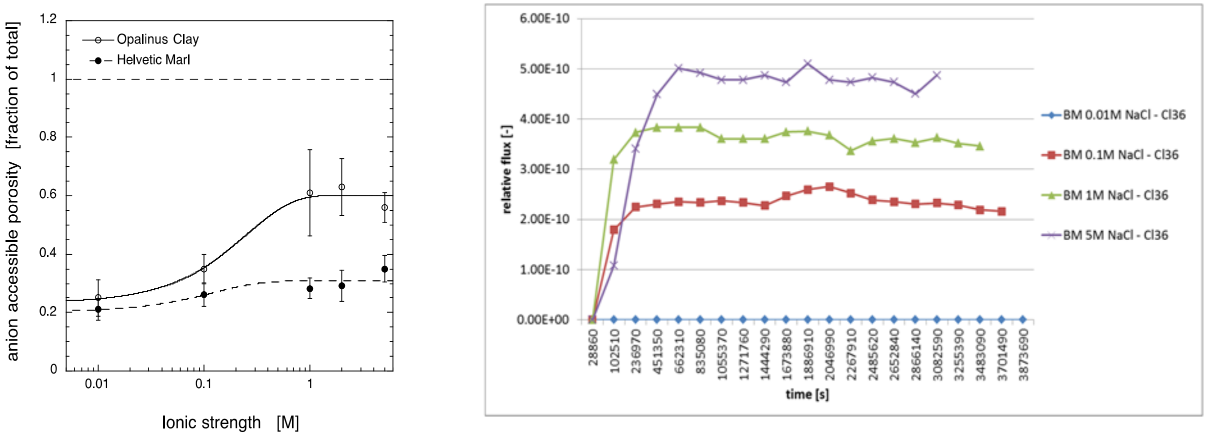


Figure 4.19: a) Effect of Ionic Strength on the Anion Accessible Porosity of Opalinus Clay and Helvetic Marl. The Accessibility is Given as Fraction of the Total Porosity; and b) Anion Diffusion Experiment on Blue Mountain Samples with Varying Ionic Strength. The Flux is Relative to the Total Tracer $^{36}Cl^{-}$ Concentration in the System Plotted

4.2.8 Chlorine and Bromine Isotopic Analyses of Groundwaters from the Bruce Site

Groundwater samples from three zones of two deep boreholes, DGR-3 and DGR-4, at the Bruce nuclear site were analyzed in 2014 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 and Guelph formations, 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 found in the Niagara tectonic structural block, southeast of the Algonquin arch. 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 value (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 δ^{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 may be very old, as their isotopic compositions have been maintained since emplacement during regional basinal fluid events occurring in the early Paleozoic (Ziegler and Longstaffe 2000a, 2000b; Bailey 2005).

Phase II work in 2015 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). This work is on-going and will be summarized, along with the groundwater results, in a technical report for the NWMO late in 2016.

4.2.9 Evolution of Deep Groundwater Systems

NWMO continues to develop numerical methods to assess and quantify the robustness of site characterization data, and predict groundwater flow and transport over geologic timescales, as relevant to the safety case. Numerical groundwater models provide a framework to assemble and integrate geosphere data. These geosphere data, when synthesized into a 3D geosphere conceptual model, form the basis for integrated groundwater systems models, which provide a quantitative assessment of suitability and facilitate a full understanding of the influences of geosphere factors such as topography, surface water features, and fracture geometry and interconnectedness.

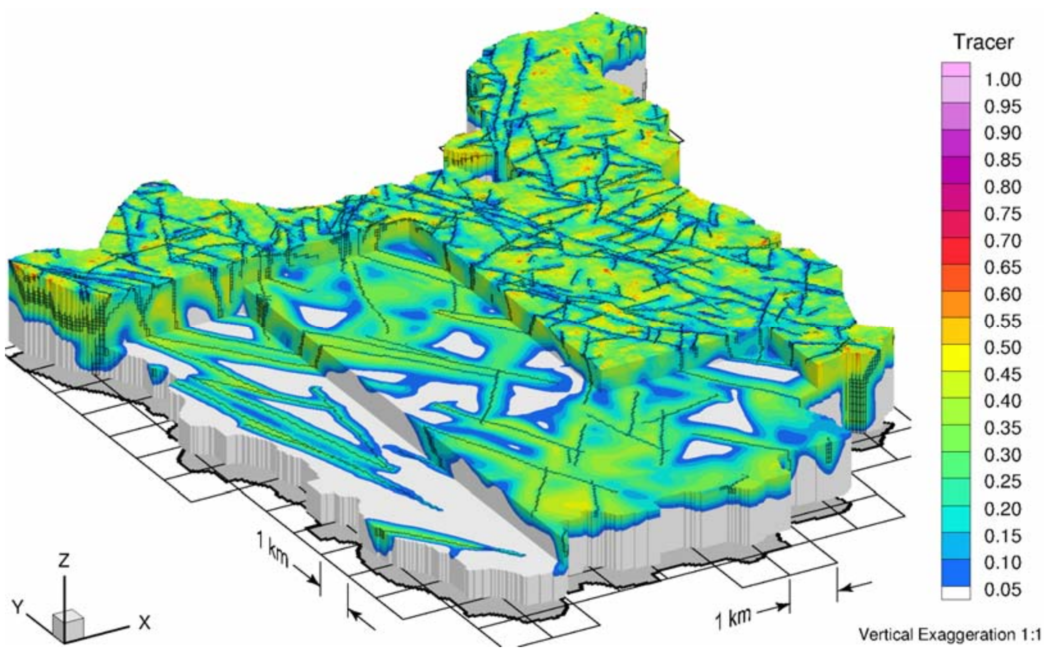


Figure 4.20: Tracer Migration at 120 Thousand Years for the Peltier Paleoclimate Boundary Conditions (fr-base-paleo-peltier)

Research investigations into the long-term behaviour of groundwater systems at depth were continued in 2015 at the University of Waterloo. The influence of surface boundary conditions on groundwater systems during glacial advances and retreats was undertaken to illustrate the long-term evolution and stability of a crystalline geosphere to external perturbations. The computational model used for the groundwater analyses was HydroGeoSphere (Aquanty 2013). For the studies conducted, the distribution of fractures was developed using MoFrac. These analyses were done through the use of multiple glacial boundary condition time-series datasets. For glacial boundary conditions over the past 120,000 years, the datasets include scenarios representing cold and warm based ice sheets (Peltier 2002), as well as an updated boundary condition dataset representing the current best estimate (Stuhne and Peltier 2015). Depth of surficial recharge (as a proxy for meltwater recharge) was used to illustrate the influence of glaciation on the groundwater systems (Figure 4.20).

4.3 MODELLING PROGRAMS

4.3.1 Reactive Transport Modelling

Reactive transport modelling is a useful approach for assessing long-term geochemical stability in geological formations. For example, reactive transport modelling can be 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 cause groundwater salinity (density) to vary 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 between 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). The code enhancements included: 1) calculation of ion activity correction in high ionic strength (up to 20 mol/L) solutions using the Harvie-Möller-Weare model, which is based on Pitzer equations; 2) calculation of fluid density for high ionic strength solutions; 3) one-dimensional hydromechanical coupling 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) 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, Flotran, and COMSOL & MCOTAC) and with *in situ* experimental data. For the benchmarking tasks, excellent agreement was achieved with other modelling groups using other reactive transport codes.

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

Figure 4.21). ParMIN3P-THCm is able to deal with the significant computational burden of reactive transport simulations involving large spatial scales and long timeframes.

In 2014, a three-year research program was initiated to further develop MIN3P-THCm to enhance model capabilities for simulation of reactive transport on the regional or basin scale. The model enhancement includes implementing (i) unstructured computational grids to more effectively simulate reactive transport in complex geological geometries, such as inclined bedrock layers in sedimentary basins; (ii) a new biogeochemical sulfate reduction model to account for the inhibition effect of hypersaline solutions on the bacterial dissimilatory reduction of sulfate; and (iii) new features to aid the assignment of rock type dependent material properties, the corresponding flow and geochemical initial conditions, and transient 3D boundary condition assignment of the ice sheet thickness contribution for the glaciation/deglaciation cycles. The enhanced code will be applied to simulate reactive transport processes on the basin scale.

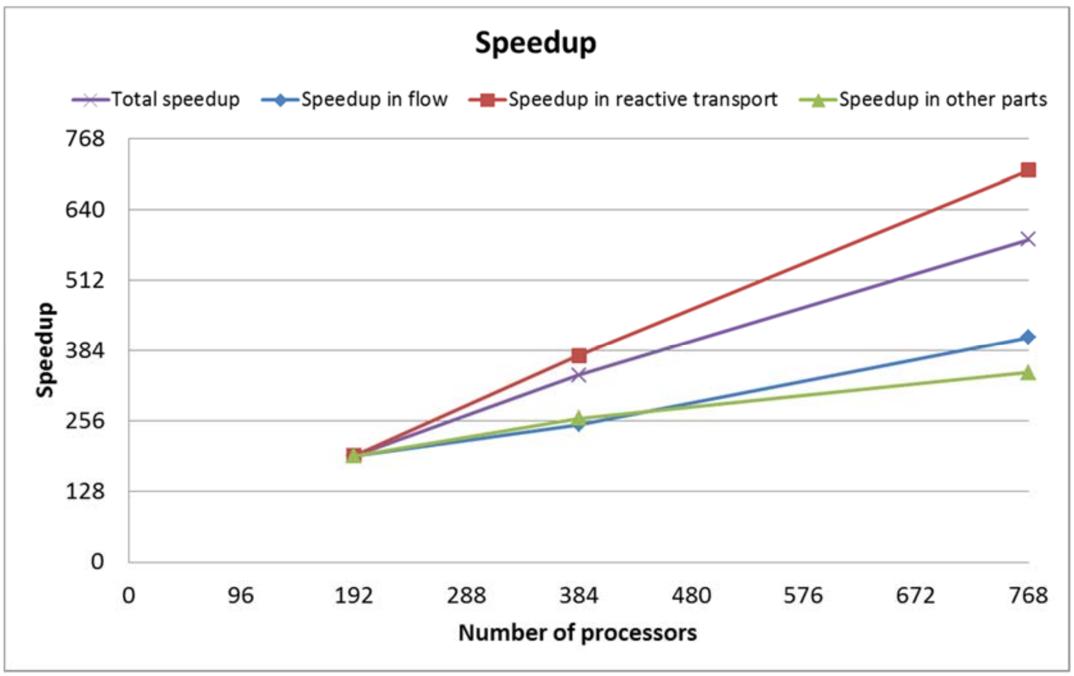


Figure 4.21: Speedup of MPI Parallel Version ParMIN3P-THCm for Flow and Reactive Transport in a Sedimentary Basin, Executed on the WestGrid Jasper Cluster, Total Degrees of Freedom is 103,680,000

In addition, MIN3P-THCm 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, 2015b 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 management 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).

4.4 INTERNATIONAL ACTIVITIES

4.4.1 Mont Terri Project, Switzerland

The experiments being conducted at Mont Terri are highly relevant to NWMO site characterization, engineering and safety assessment activities for sedimentary rock formations. Involvement in the Mont Terri Project allows NWMO to participate in state-of-science research in a state-of-the-art URL in collaboration with numerous international project partners with extensive expertise in repository engineering, research and design.

Full-scale Emplacement (FE) Experiment

In 2015, NWMO was a project partner of several experiments in the Mont Terri Rock Laboratory, Switzerland. One of these experiments was the FE or Full-scale Emplacement 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 engineering barrier system (EBS). The general arrangement of the experiment is shown on Figure 4.22 and the experiment is carried out at a 1:1 scale. The behaviours of backfill material and rock under the influence of temperature are monitored as the containers are heated to simulate the heat generated by radioactive waste. Measurements will be made over the next 15 years. The placement of heating elements and backfilling of the tunnel has been completed. A concrete bulkhead has been casted near the portal of the tunnel. Several hundred sensors were installed to monitor temperature, porewater pressure, water content, suction, and deformations and stresses within the bentonite backfill and host rock throughout the entire experiment duration. Figure 4.23 shows the layout of instruments around Heater 2 (Garitte 2016). Since early 2015, instrumentation data have be collected on the experiment simulating post-closure conditions. All data is currently being complied and will be input into THM analysis to simulate post-closure conditions. The predictions of the system evolution for the experiment reveal good qualitative agreement with observations in the first year of monitoring (Garitte 2016). Calibrations of THM parameters of bentonite backfill and host rock are currently in progress to gain good understanding of the underlying processes (Figures 4.24 and 4.25).

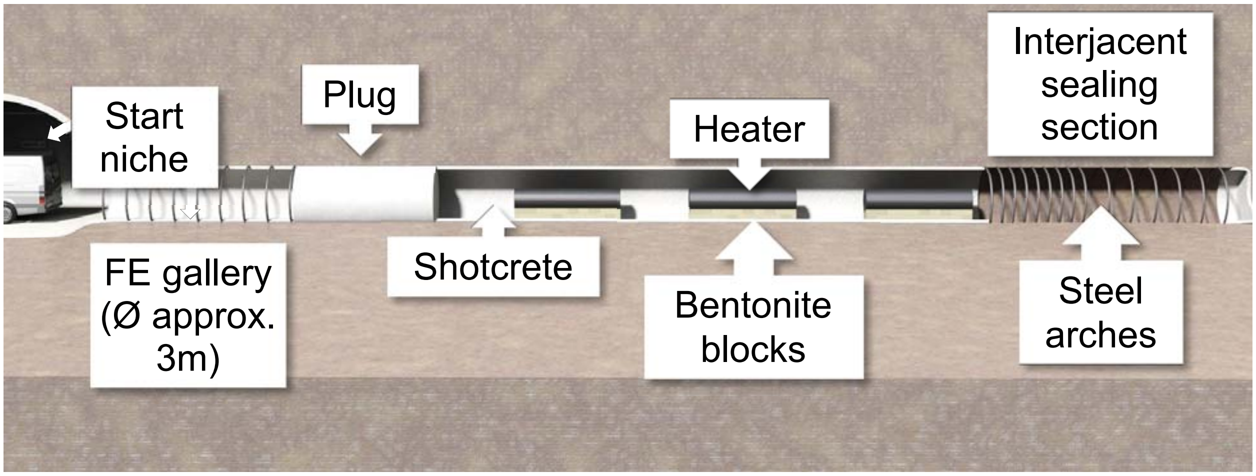


Figure 4.22: Visualization of Final Arrangement of FE Experiment at Mont Terri Rock Laboratory (Vogt 2013)

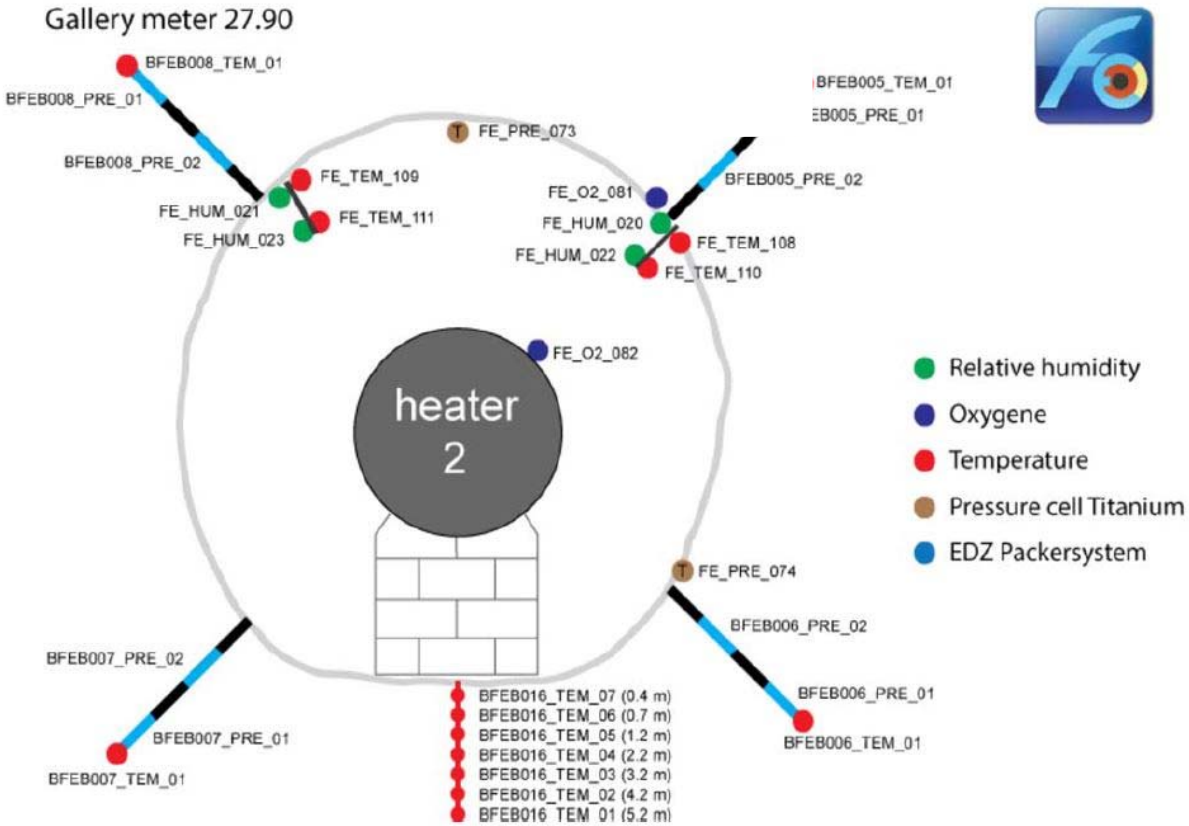


Figure 4.23: Layout of Instruments Around Heater 2 (middle; Garitte 2016)

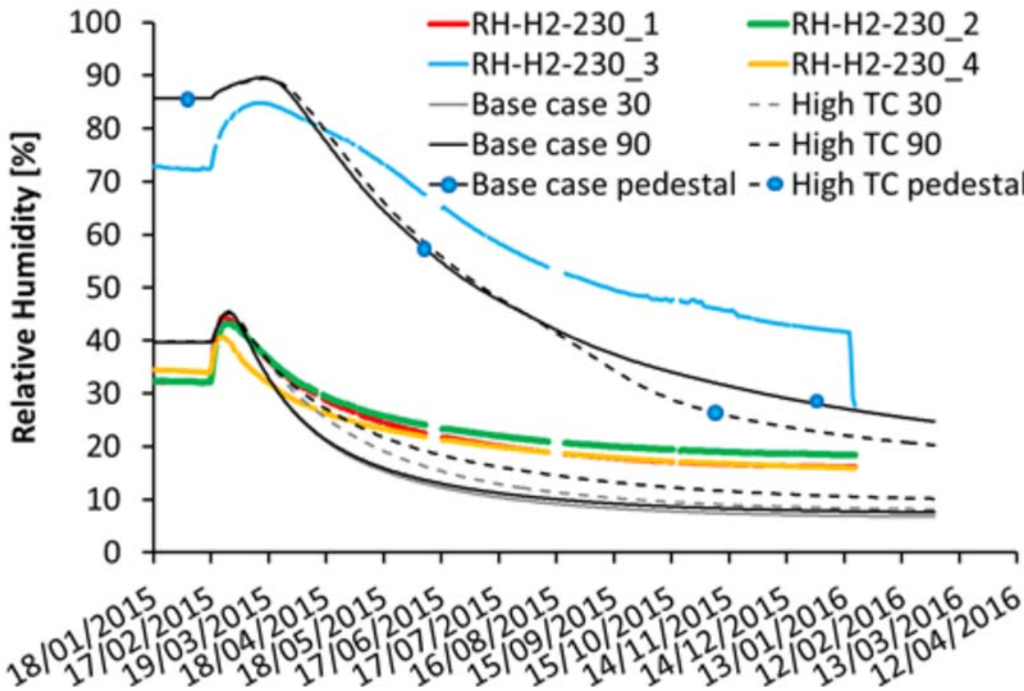


Figure 4.24: Comparison of Predicted and Observed Relative Humidity

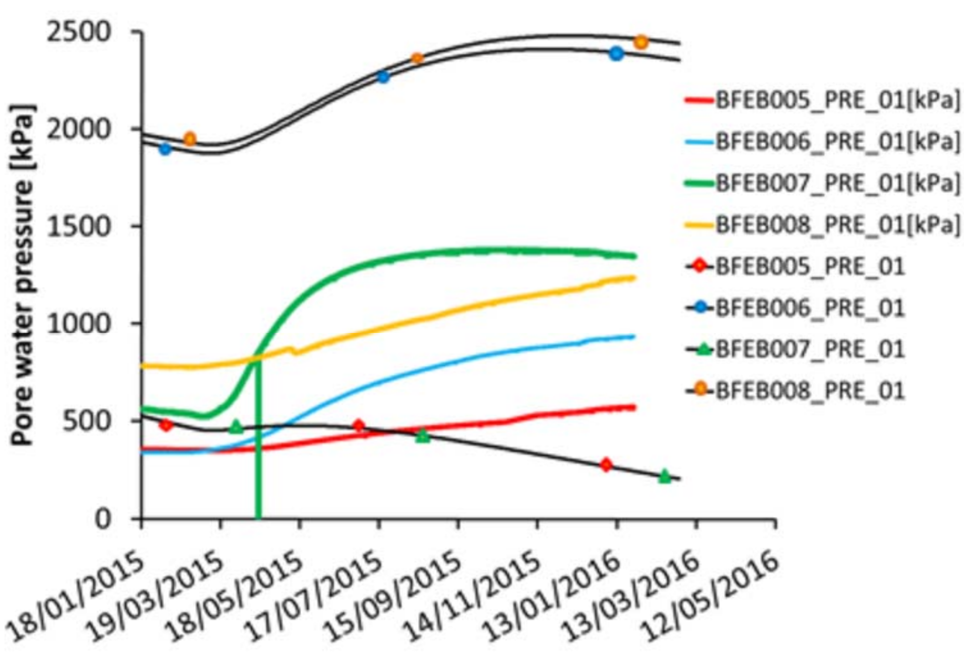


Figure 4.25: Comparison of Predicted and Measured Pore Water Pressure

Deep Borehole (DB) and Porewater Characterization (DB-A)

The goal of the Deep Borehole (DB) experiment 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 under-lying aquifer formations. The DB Experiment is now in the modelling and data interpretation phase.

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 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 He. Core samples for the analyses were collected adjacent to one another during drilling (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 allows a direct comparison of results derived from the methods indicated above, as well as assessments of method applicability and potential analytical artefacts. Meetings to discuss the results and findings were held between the researchers in 2015, and a technical report documenting the results of the benchmarking exercise will be completed in 2016. A second report detailing the results of the aquifer interface investigation is also expected in 2016.

4.4.2 Glacial Systems Model

Glaciation associated with long-term climate change is considered the most intense external perturbation to a DGR. Potential impacts of glacial cycles on a deep geologic repository include: increased stress at repository depth caused by glacial loading; penetration of permafrost to repository depth; recharge of oxygenated glacial meltwater to repository depth; and 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 NWMO's studies into the impact of glaciation, these 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 (Figure 4.26).

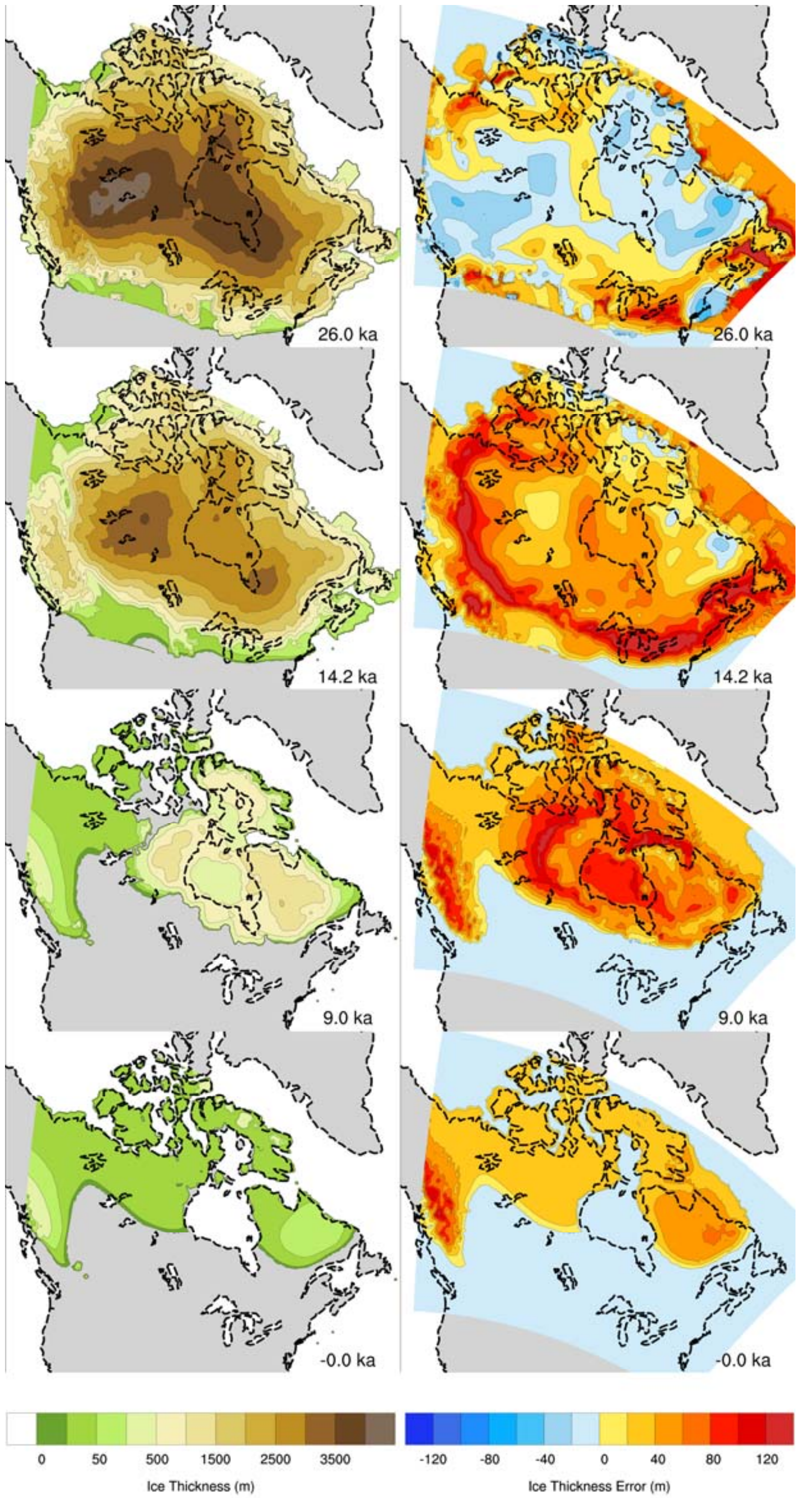


Figure 4.26: Reference Solution Ice Thickness, I (left), and error, _I (right), at t = 26 kyr BP (LGM),14.2 kyr BP, 9 kyr BP, and present

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. 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 kyr 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 are illustrated as well in Figure 4.26.

4.4.3 Fracture Network Software for Site Characterization

In crystalline rocks, the presence and distribution of fracture zones in the geosphere will strongly influence groundwater system stability and evolution. The predominant pathway for solute migration will be through the interconnected network of permeable fractures. Therefore, it is important to be able to both characterize and represent these structural features in three dimensions using structurally possible, geostatistically representative fracture networks that are directly derived from field-data collected during surface and sub-surface investigations.

Previously, fracture network models have been created using legacy software known as FXSIM3D for the Whiteshell Research Area (Srivastava 2002a) and for the Sub-regional Shield Flow System case study (Srivastava 2002b). This fracture network model was subsequently used for the Used Fuel Repository Conceptual Design and Postclosure Safety Assessment in Crystalline Rock (NWMO 2012). 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 to be directly linked 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 using purposely 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 4.27.

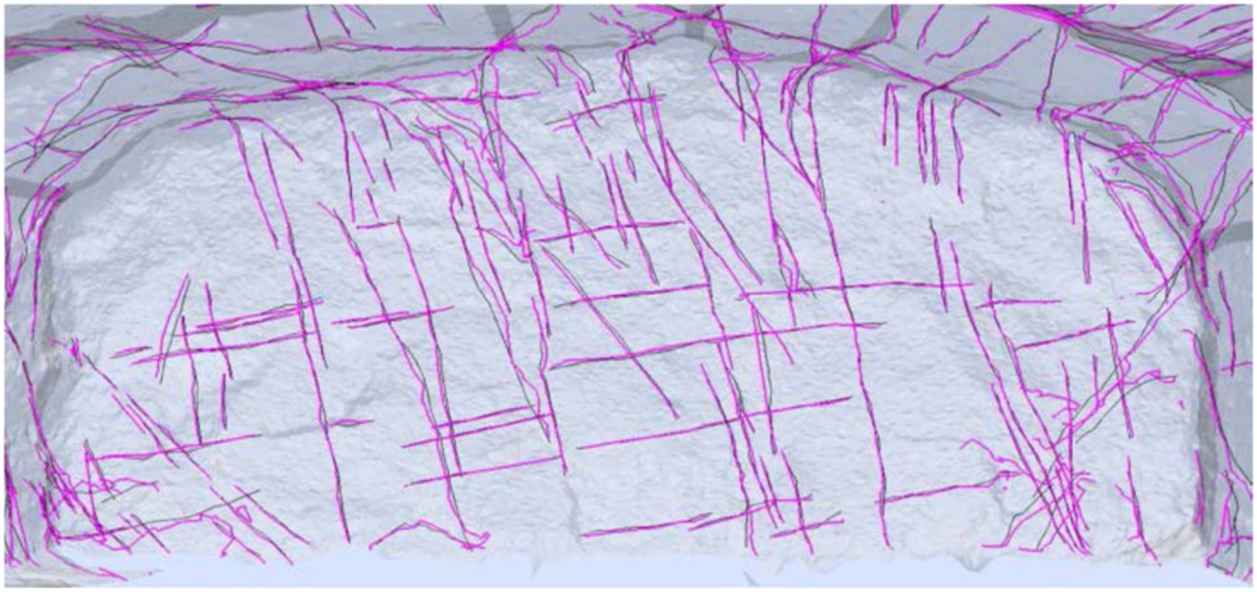


Figure 4.27: Comparison of Field and Generated Fracture Traces for Tunnel Wall

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 2015 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 waste form
Robust container
Clay seals
Low-permeability host rock
Spatial extent and durability of host rock formation
Stable chemical and hydrological environment

5.1 MODEL AND DATA DEVELOPMENT

5.1.1 Wasteform Modelling

The first barrier to the release of radionuclides is the used fuel matrix. 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.

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

The 2015 program on UO_2 dissolution continued at Western University and included:

- Application of the previously developed model to ascertain the influence of radiolytic H_2 on the fuel corrosion rate;
- Determination of the influence of H_2O_2 on carbon steel corrosion; and
- Study of the effect of pH on the corrosion of UO_2 fuel.

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

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

In 2014, a two-dimensional model was developed to simulate the UO_2 corrosion behaviour within fuel cracks of various dimensions. Although the model includes a complete set of alpha-radiolysis products (e.g., H_2O_2, $H^{\bullet}$, $OH^{\bullet}$) and reactions, calculations with the model indicated that a simplified alpha-radiolysis model which only accounts for the radiolytic production of H_2O_2 and H_2 provides a reasonably accurate simulation and is a time-efficient alternative to using a full alpha-radiolysis reaction set (Wu et al. 2014a, 2014b). Results using the simplified model are presented below.

The two-dimensional arrangement used to simulate a rectangular fuel crack and the fuel/groundwater interface is shown in Figure 5.1. The dimension of the crack is determined by its width and depth. Alpha radiolysis is assumed to occur uniformly within a thin layer of solution (about 13 μm, the average penetration distance of alpha particles in water) at the fuel surface. No radiolysis products are produced beyond this thin layer. The diffusion zone is defined as a water layer on the fuel surface, through which species can diffuse to, or from, the fuel surface. Beyond this zone, uniform concentrations are assumed to prevail. Model results for cracks of various dimensions are illustrated in Figure 5.2 which shows the critical [H_2], which is the minimum bulk H_2 concentration required to completely suppress fuel corrosion, as a function of the time after placement of the fuel in the repository. As expected, the critical [H_2] decreases markedly with time. The increase in the critical [H_2] over the first 100 years reflects the accumulation of alpha-emitters as a consequence of the short-term betta/gamma decay of radionuclides within the fuel.

Figure 5.2 suggests that when cracks are sufficiently deep, the critical [H_2] increases only slightly as the crack depth increases. Additional model calculations show that the radiolytic H_2 generated within deep cracks plays an important role in inhibiting fuel corrosion. This is illustrated in Figure 5.3 in terms of the UO_2^{2+} flux at the crack bottom, which is a measure of the used fuel dissolution rate at this location. This figure demonstrates that radiolytic H_2 is important in controlling fuel corrosion in deep narrow cracks in which transport of hydrogen from the bulk solution is slow, thereby significantly reducing the requirement for H_2 from steel corrosion in the suppression of fuel corrosion.

Finally, work is underway to validate the dissolution model by comparing calculated fuel dissolution rates for different alpha-radiation field strengths with measured dissolution rates (e.g., Figure 25 in Poinssot et al. 2005).

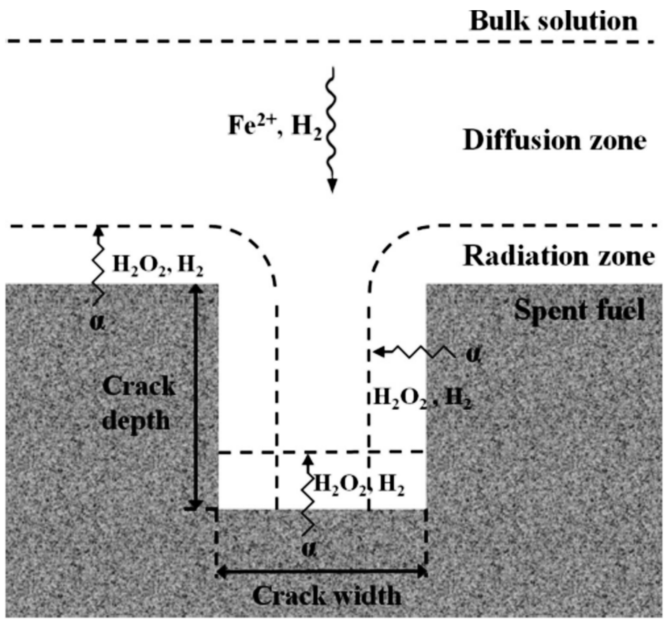


Figure 5.1: Model Arrangement Showing a Cross-section of the Fuel/solution Interface for Simulation of Radiolytic Corrosion Inside a Crack in a Fuel Pellet

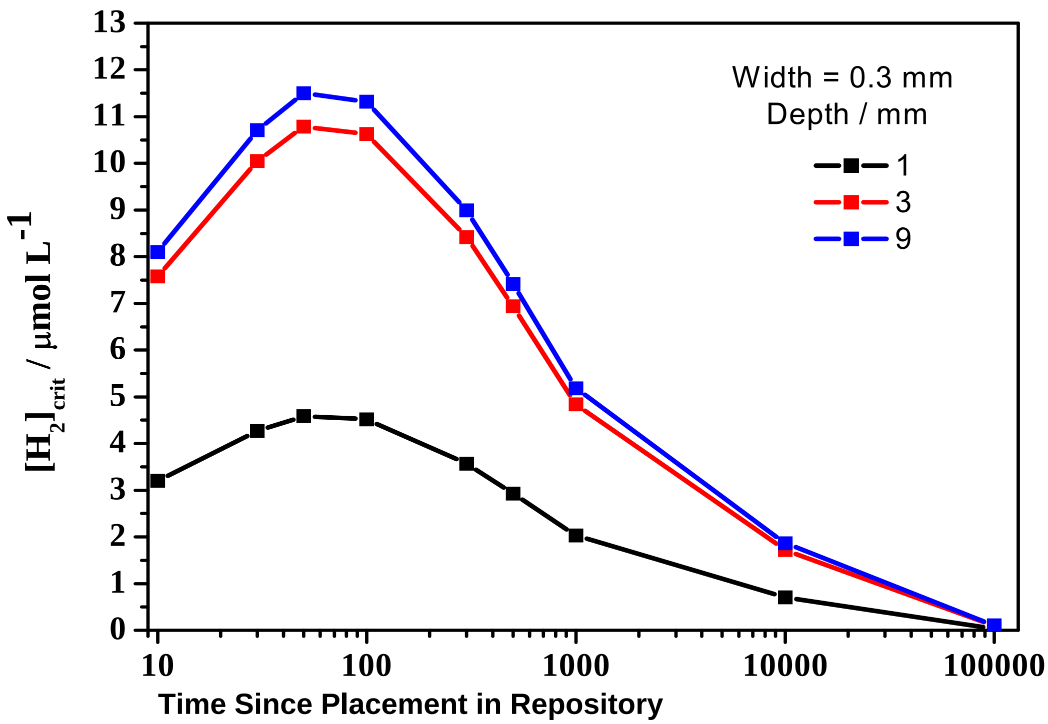
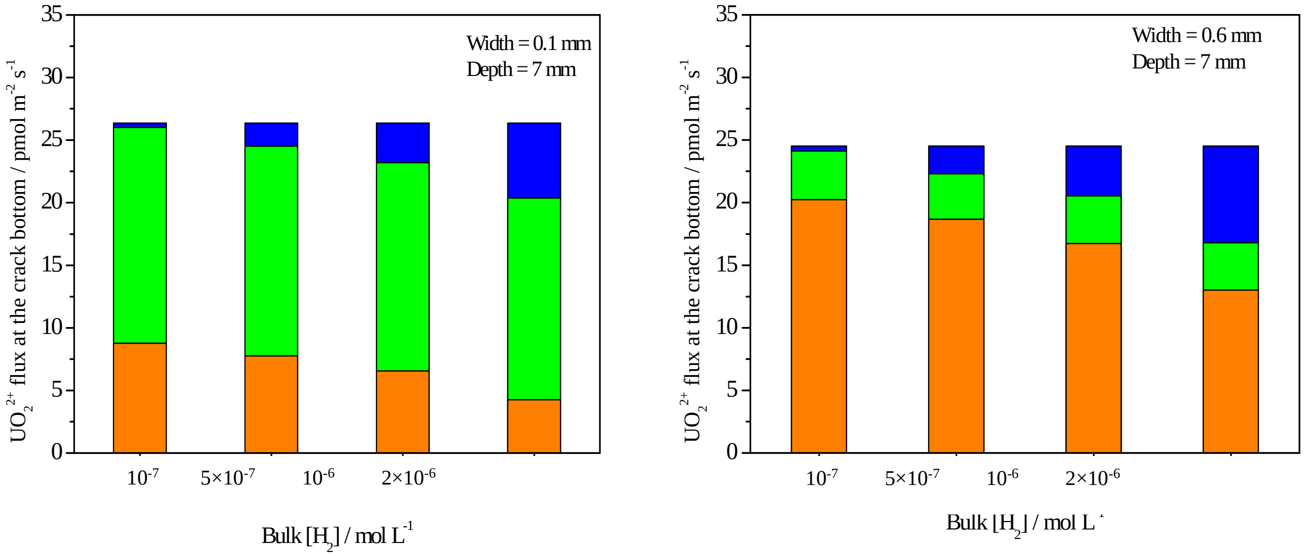


Figure 5.2: The critical [H_2] as a Function of Time Since Placement of the Fuel in the Repository for Various Crack Depths and a Crack Width of 0.3 mm.



Note: the alpha radiation dose rate in these model calculations is 9.03x105 Gy/a.

Figure 5.3: UO22+ Flux on Crack Bottom as a Function of Bulk [H2] In a Narrow Crack (Left) and Wide Crack (Right). The Total Flux is The Corrosion Rate Without any H2, The Flux In Orange is the Corrosion Rate with Both External (I.E., Bulk) and Radiolytic H2 Present, The Flux in the Green Colour is the Corrosion Rate Suppressed by Radiolytic H2 and the Flux in the Blue Colour is the Corrosion Rate Suppressed by External H2.

5.1.1.2 Corrosion of Carbon Steel in the Presence of H_2O_2

In order for H_2 (and Fe^{2+}) generated by carbon-steel corrosion to control redox conditions inside a breached used fuel container (see above), it is necessary for the steel vessel to continue to corrode. A possible mechanism by which the steel could stop corroding, and H_2 production suppressed, is passivation of the steel by reaction with radiolytic H_2O_2. Consequently, the influence of H_2O_2 on the corrosion of carbon steel was investigated under anaerobic conditions (i.e., oxygen concentrations in the ppb level) (Hill et al. 2015). In particular, the corrosion of carbon steel in 0.1 M NaCl solutions, in the presence of H_2O_2 concentrations in the micro-molar range, was investigated using corrosion potential measurements, linear polarization resistance measurements and surface analyses.

Solutions with H_2O_2 concentrations in the micro-molar range were found to accelerate steel corrosion, leading to formation of Fe(III)-containing corrosion product deposits. Under anaerobic conditions, active steel corrosion producing Fe^{2+} and H_2 was maintained up to $[H_2O_2]$ = 6 μM, the maximum concentration studied.

The fuel dissolution model (see above) was used to determine the H_2O_2 concentration possible in a breached used fuel container in a repository. These calculations indicated that it would be highly unlikely that H_2O_2 concentrations would reach the μM level at which the influence of H_2O_2 on steel corrosion would become significant. Based on the results of this work, it can be concluded that active steel corrosion will be maintained inside a failed used fuel container and that soluble steel corrosion products (Fe^{2+} and H_2) will be available to supress fuel corrosion and radionuclide release.

5.1.1.3 Influence of pH on Fuel Corrosion

Studies of the cathodic reduction of H_2O_2 on UO_2 indicate that the mechanism and kinetics of the reaction are unchanged over the pH range 4 to 9 (He et al. 2012). Under natural corrosion conditions the H_2O_2 reduction reaction would be coupled with the oxidation and dissolution of the fuel. Consequently, it is expected that fuel dissolution would be largely independent of pH for pH values in the range 4 to 9. A series of electrochemical experiments were begun in 2015 to verify the expected modest influence of pH (over the pH range 6 to 10) on fuel dissolution.

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 3.3.2.

5.1.2.1 Radionuclide Solubility

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

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

Potential Canadian repository groundwater conditions range from relatively freshwater to highly saline. Currently, both the Pitzer (Specific-ion Interaction) and SIT (Specific Ion Theory) approaches are used to calculate solubilities at high salinities. While the Pitzer approach is generally considered better at very high salinities, it currently has a more limited thermodynamic dataset. Reference solubility calculations were determined using both Pitzer and SIT approaches (Duro et al. 2010).

Current work (see below) is focused on developing the thermodynamic database to support future site-specific calculations

5.1.2.2 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. was defined with two primary objectives: 1) updating the Phase II actinide thermodynamic databases, including technetium; and 2) preparation of state-of-the-art reports on thermodynamic considerations for cement materials, thermodynamic considerations for actinide elements in high ionic strength aqueous solutions, and thermochemical extrapolation of data to non-standard state temperatures. These projects are underway.

The NEA TDB project provides high-quality datasets for a limited number of elements. This information is important, but is not sufficient on its own, as it does not address the full range of elements of interest. Also, the NEA TDB has, until recently, focused on low salinity systems in which activity corrections are described using SIT parameters. Due to the high salinity of groundwaters and porewaters (with an ionic strength of up to 5 M) 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. An assessment of the THEREDA database for the oceanic salt system (for which there is appreciable data over a wide temperature range) was carried out in 2015. This indicated that the THEREDA model provides a good representation of experimental data for many subsystems involved.

In order to address gaps in the high-salinity thermodynamic data relevant to an APM repository, the NWMO is co-sponsoring the newly created 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 will start in 2016.

5.1.2.3 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. 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 its saturating phase.

5.1.2.4 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 2015, 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 and four were used: deionized water, approximately 11 g/L TDS, approximately 223 g/L TDS, and approximately 335 g/L TDS.

The tests evaluate the following:

- Compaction/fabrication properties of the materials (to Modified Proctor density);
- Consistency limits (Atterberg Limits) and free swell tests;
- Density of as-fabricated material;
- Moisture content of as-fabricated material
- Mineralogical/chemical composition, including three independent measurements of montmorillonite content using different laboratories;
- Mineralogical/chemical composition of the materials exposed to brine for an extended period of time;
- Swelling pressure;
- Saturated hydraulic conductivity;
- 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;
- Mechanical parameters including Shear Modulus (G), Bulk Modulus (K) and Young's Modulus (E); and
- Thermal properties including thermal conductivity and specific heat capacity.

Testing for the first 8 items has been completed and measurements are consistent with anticipated values, based on literature information available for similar materials.

In 2014, 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 5.4 shows the change in unconfined compressive strength of LHHPC samples with curing age. At 270 days of curing, the unconfined compressive strength of these samples approaches 95-100 MPa. These initial tests show that the LHHPC and asphalt-based materials can provide a low hydraulic permeability barrier to groundwater movement. In addition, LHHPC can provide good mechanical support to overlying materials.

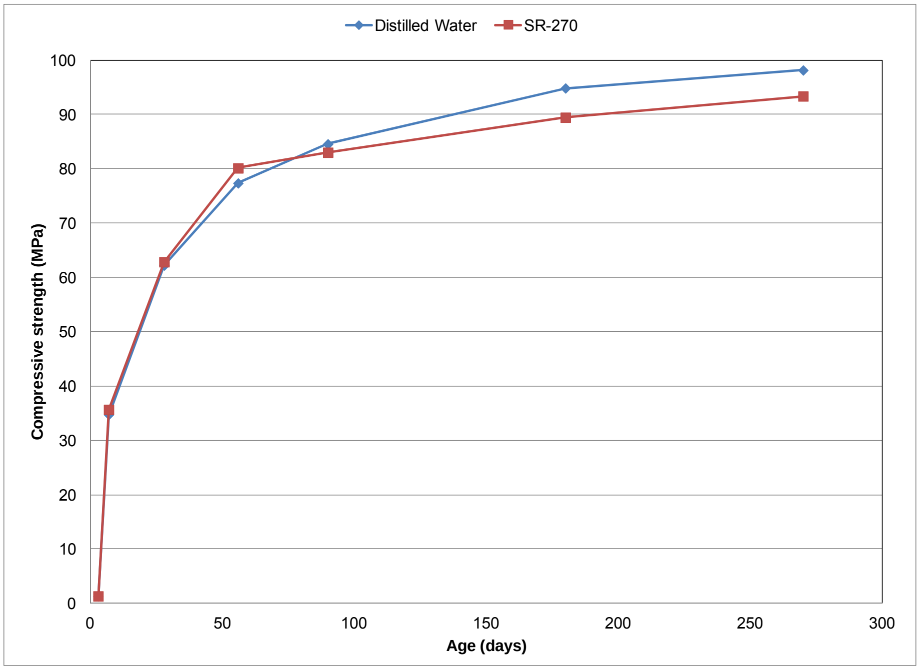


Figure 5.4: Unconfined Compressive Strength Results for LHHPC

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 are being 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 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. The performance of the final optimized mixes will be similar to, or exceeding, the original reference formulation. Optimization will be completed in 2016.

5.1.2.5 Thermal Modelling of the Mark II Container

The NWMO is assessing the safety performance of the Mark II Engineered Barrier System (see Section 3.2). 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 (2015) describes the analysis methods, assumptions and results obtained in calculations performed to assess fuel temperatures inside a Mark II container, assuming the used fuel bundles have a decay period of 30 years with a discharge burnup of 220 MWh/(kgU). A variety of external boundary conditions are considered:

- The Mark II container in air;
- The Mark II container inside the buffer box in air;
- The Mark II container inside the buffer box, backfilled in a hypothetical crystalline rock repository; and,

- The Mark II container inside the buffer box, backfilled in a hypothetical sedimentary rock repository.

The temperatures in the fuel bundle, in the container, in the buffer box and in the rock for different cases are analyzed and selected results are shown in Figure 5.5: and Figure 5.6: Figure 5.7.

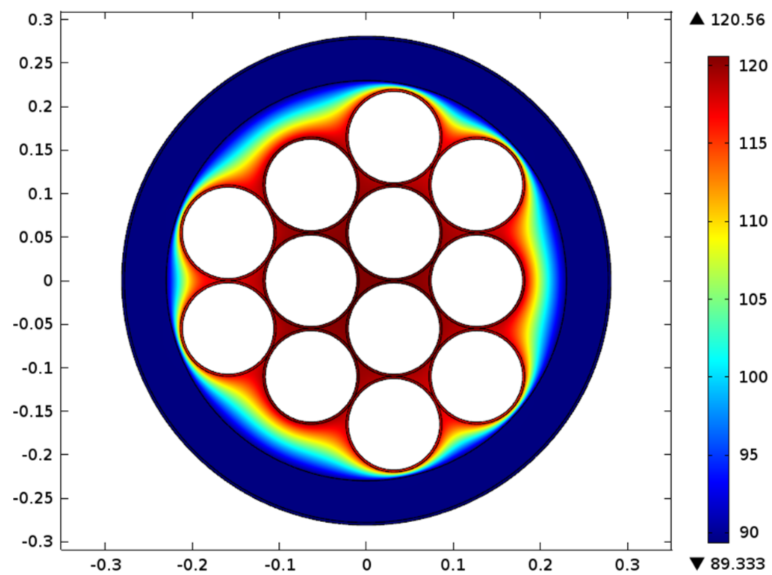


Figure 5.5: Temperature (°C) Across the Middle Section of a Mark II Container After ~15 years in a Hypothetical Crystalline Repository

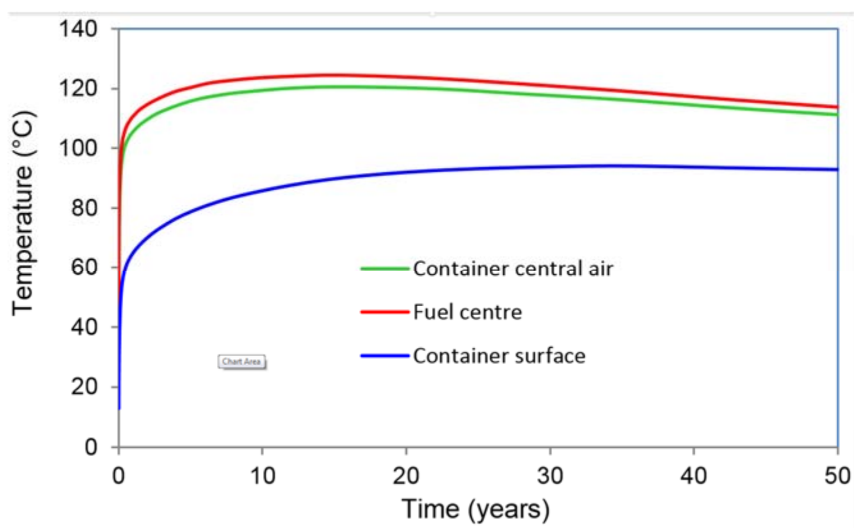


Figure 5.6: Figure 5.7: Mark II Container Temperatures in a Hypothetical Crystalline Repository

The overall conclusion is that the maximum temperature of 30-year-old fuel with a burnup of 220 MWh/(kgU) will be less than 58°C during handling of the container, about 73°C during handling of the buffer box during placement, and about 123°C after placement in a crystalline or sedimentary rock repository.

5.1.3 Geosphere Modelling

5.1.3.1 Probabilistic FRAC3DVS-OPG and SYVAC3-CC4 Modelling

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

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

The SYVAC3-CC4 model (NWMO 2012b) is simplified and approximate when compared to the more sophisticated FRAC3DVS-OPG code; however, the long run times associated with the FRAC3DVS-OPG model (Therrien et al. 2010) preclude the use of this tool for probabilistic studies where, typically, 120,000 simulations are performed. With the advent of relatively inexpensive processing power and cluster or parallel computing, running detailed models probabilistically is becoming more feasible.

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

The results of this study (Avis and Sgro 2013) indicate that it might be feasible to use FRAC3DVS-OPG for probabilistic studies. An expansion of this work program was completed in 2015 which successfully demonstrated that probabilistic safety assessment calculations can be undertaken by coupling a FRAC3DVS-OPG geosphere model and an AMBER (Quintessa 2013) biosphere model. This work may be once again expanded on to test the feasibility of coupling probabilistic vault, geosphere, and biosphere models in the future.

5.1.4 Biosphere Modelling

5.1.4.1 Non-Human Biota

In 2008, a screening methodology was developed for assessing the potential postclosure impact of a repository on specific representative non-human biota. The methodology involved the estimation of reference No-Effect Concentrations (NECs) for radionuclides in environmental media to which biota are exposed. Because of the conservative nature of the assumptions used to derive NECs, there was confidence that, despite uncertainty in environmental concentrations, there would be no significant ecological effect on biota as long as the NECs were not exceeded. The NECs were developed for a set of 12 radionuclides, including the major dose contributors identified in the Canadian Third Case Study and other safety assessments. The NEC approach is also used in 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 the transfer factor approach (as with the NECs) and concentration ratio approach (as in the ERICA tool). The model considers the effects of 45 radionuclides on a wide range of species that are representative of the main taxonomic groups found in 3 different Canadian ecosystems (the southern Canadian Deciduous Forest, the Boreal Forest and the Inland Tundra). A technical report documenting the 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).

5.1.4.2 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.

5.1.4.3 Participation in BIOPROTA

BIOPROTA is an international collaborative program created to address key uncertainties in long-term assessments of contaminant releases into the environment arising from radioactive waste disposal. Participation is aimed at national authorities and agencies with responsibility for achieving safe and acceptable radioactive waste management practices, including both regulators and operators. Overall, the intention of BIOPROTA is to make available the best sources of information to justify modelling assumptions made within radiological assessments constructed to support radioactive waste management. These projects are typically co-sponsored by several national waste management organizations. NWMO supported the following projects, which were completed in 2015.

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 both on the behaviour of C-14 once in the surface environment and on approaches to assessment. In 2013, a refereed paper on this work was published in the Radiocarbon Journal. In 2014, a workshop on this topic was held in France and its workshop report was subsequently issued (BIOPROTA 2014). This phase of C-14 work is complete; however, new collaboration activities have been proposed by BIOPROTA for 2016.

Scales of Post-closure Assessment Scenarios (SPACE)

The purpose of this work program was to examine the effect of temporal and spatial scales when assessing the post-closure radiological impacts of radioactive waste repositories on representative wildlife species. The variety of plants and animals in the natural environment is immense and, as such, the scope of the project was necessarily limited to the general types of plants and animals representative of temperate terrestrial ecosystems. A report on this work was published in early 2015 (BIOPROTA 2015).

5.1.5 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	10	Reference integrated system model
FRAC3DVS-OPG	1.3	Reference 3D groundwater flow and transport code
T2GGM	3.1	3D two-phase gas and water flow code
AMBER	5.7.1	Generic compartment modelling software
COMSOL	5.0	3D multi-physics finite element modelling software
PHREEQC	3.0.6	Geochemical calculations code
MICROSHIELD	9.05	Radioactive shielding and dose code
ORIGEN (SCALE)	4.2	Used fuel inventory calculations
MCNP	5.0	Criticality and shielding assessments

The following sections describe code-related activities conducted in 2015.

5.1.5.1 Updates to SYVAC3-CC4

Software updates to the integrated system model SYVAC3-CC4 (NWMO 2012b) were initiated in 2013 and continued through 2014 and 2015. The purpose of these updates was to add several additional code features and correct minor errors (e.g. output for some parameters). New SYVAC3-CC4 v10 code features include:

- Consistent handling of biosphere degassing and deposition pathways;
- Additional biosphere plant types;
- A new leaching wasteform;
- A new simplified well model;
- An update to the gas transport model; and
- An update to the geosphere and near-field sorption models.

Testing and development of the updated SYVAC3-CC4 model will continue in 2016.

The SYVAC3-CC4 validation efforts were most recently documented in Garisto and Gobien (2013). New tests completed in 2015 using the current version 9.1 include:

- 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,
- Comparison of the container release model in CC4 for the Mark II container and repository design with COMSOL v5.0.

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 ongoing effort in 2016.

5.1.5.2 Updates to T2GGM

T2GGM is a three-dimensional simulator that couples the Gas Generation Model (GGM) and TOUGH2. GGM models the detailed generation of gas within the repository due to corrosion and microbial degradation of the metals and organics present. TOUGH2 models the subsequent two-phase transport of the gas through the repository and geosphere. The coupling of GGM and TOUGH2 allows the interactions between gas generation/pressure and water saturation in the repository to be represented explicitly. A revised version of T2GGM, version 3.2 (Suckling et al. 2015), was released in 2015. The new T2GGM (v3.2) includes the following updates:

- FLAC3D integration. With the integration with FLAC3D, a standalone 3D geotechnical modelling tool, T2GGM is now able to run coupled 3D thermo-hydro-mechanical (THM) modelling.
- Pressure-dependent permeabilities. The implementation of this new feature is based on a pre-defined static stress field.
- An improved convergence-failure handling algorithm. With this improvement, T2GGM is now able to automatically restart when a convergence failure is detected.
- Peng-Robinson gas properties. This new feature accounts for super-compressibility of gases (e.g. methane) at high pressures by incorporating compensation for density of non-ideal gases.
- The capability to link models of different scales.
- An improved approach for corrosion calculations within a partially saturated placement room.
- An alternative mechanism to calculate relative humidity. The new mechanism will enable T2GGM to account for the lowering of vapour pressure by bentonite suction; specifically, using capillary pressure to calculate relative humidity based on Kelvin’s equation.
- An additional Graphics Processing Unit (GPU) solver. This may substantially improve the T2GGM simulation speed.

5.1.5.3 Updates to Miscellaneous Codes

New versions of two of the SYVAC3-CC4 pre and post-processing tools SINGEN (version 3.3) and SYVIEW (version 1.3) were completed in 2015. These updates allow the software tools to function correctly with the new version of SYVAC3-CC4.

The Human Intrusion Model was also updated to reflect changes in the reference container and repository designs. This updated model is described in Medri (2015c).

5.2 SAFETY STUDIES

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

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

5.2.1 Preclosure Studies

5.2.1.1 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 components of this preliminary assessment are: 1) the activity list that identifies the worker exposure situations during operation of the Used Fuel Packaging Plant (UFPP) and the repository and 2) calculations of neutron and gamma dose rates for these expected exposure situations. A preliminary estimation of the individual and collective doses has been developed for each concept.

The main findings of this preliminary assessment are that: a) workers involved in the receipt of Used Fuel Transport Packages (UFTP) have the highest normal dose exposure; b) dose to workers in the rest of the UFPP and in the repository are much lower; and c) taking into account the results and recommendations of this assessment, the worker doses will be within applicable dose constraints. Important dose considerations are the volume of used fuel assumed to be received and processed at the UFPP (about 630 UFTPs received and a maximum of 144,000 used fuel bundles processed) and the assumptions regarding the handling and temporary storage of UFTP at the facility. Potential changes to the design and operation of the facility that could reduce the occupational doses have also been identified.

In 2016, the preliminary ALARA report (Reijonen et al. 2014) will be updated for the Mark II conceptual design to be consistent with the latest UFPP and repository designs.

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, 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 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).

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 2015, the NWMO provided funding and technical input 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, that all relevant factors are being considered.

An NEA international database of potential FEPs is being maintained to provide a comprehensive list of factors based on knowledge accumulated over many years and numerous national evaluations. Reference to this internationally recognized FEPs database is useful in that it helps ensure the NWMO FEPs are complete and consistent with international best practices. The NEA, via the Integration Group for Safety Case (IGSC), is currently updating the NEA FEPs database. In 2015, the NWMO continued to provide funding to support this activity and also reviewed the FEPs list and FEPs descriptions.

A preliminary FEPs assessment for the Sixth Case Study was carried out in 2015, and is currently being reviewed. This assessment in many respects is 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. The repository site and repository depth are the same for both case studies.

5.2.2.2 Glaciation in a Sedimentary Rock Environment

The NWMO recently 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 will be documented in a Technical Report to be issued in 2016.

5.2.2.3 Assessment of Repositories with the Mark II Engineered Barrier System

The Engineered Barrier System (EBS) is a key component of the design of the underground repository and preparation of the safety case. Recently completed post-closure safety assessments (NWMO 2012a; NWMO 2013) will be iterated to account for the Mark II EBS. This work, initiated in 2014, will build confidence in the safety cases for both crystalline and sedimentary siting scenarios, as well as support the Mark II EBS proof-testing program (see Section 3.3).

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.

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APPENDIX A: TECHNICAL REPORTS, RESEARCH PAPERS AND CONTRACTORS

A.1 NWMO Technical Reports

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A.3 LIST OF RESEARCH COMPANIES, SPECIALISTS AND UNIVERSITIES

Amec Foster Wheeler
ANCAM Solutions Company Ltd
Atomic Energy of Canada Limited
Canadian Hazards Information Services
CanmetMATERIALS
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
Southwest Research Institute
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
Virginia Polytechnic Institute and State University
Western University
York University

APPENDIX B: ABSTRACTS FOR TECHNICAL REPORTS FOR 2015

ABSTRACT

Title:	**Title: Technical Program for the Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2014**
Report No.:	**NWMO TR-2015-01**
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, E. Kremer, P. Maak, J. McKelvie, C. Medri, M. Mielcarek, A. Murchison, A. Parmenter, R. Ross, E. Sykes, T. Yang
Company:	Nuclear Waste Management Organization
Date:	April 2015

Abstract
This report is a summary of activities and progress in 2014 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 2014 are summarized below.

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

- NWMO provided research contracts and research grants to 11 Canadian universities and colleges, 3 foreign universities and supported 3 Ph.D. research projects in 2014.

- NWMO's research program published 17 NWMO technical reports and submitted 30 abstracts for presentation at national and international conferences focused on environmental radioactivity and radioactive waste management.

- NWMO continues to pursue engineering conceptual designs, canister and emplacement designs, cost estimates, transportation logistics and implementation schedules in support of APM. During the summer season, the exhibit trailer appeared in 25 events, attracting more than 1,500 visitors.

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

- The NWMO geosciences program continued to develop plans, 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.

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ABSTRACT

Title: **Non-Human Biota Dose Assessment Illustrative Results for Repositories in Crystalline and Sedimentary Rock**
Report No.: **NWMO-TR-2015-02**
Author(s): Chantal Medri
Company: Nuclear Waste Management Organization
Date: February 2015

Abstract

The basis for assessing the potential postclosure impacts of a deep geological repository on non-human biota has been evolving, particularly with the development of new data. NWMO has developed an updated model and dataset consistent with current international practice (Medri and Bird 2015). This report presents the application of this updated non-human biota dose model, using as a basis the calculated environmental media concentration outputs from recent NWMO postclosure safety assessments for hypothetical crystalline and sedimentary rock sites.

Three analysis cases were selected from each of the postclosure safety assessments: a Normal Evolution Scenario, a sensitivity study, and a Disruptive Scenario. For mammals and birds, the dose rates have been calculated using two different radionuclide partitioning methods: Concentration Ratio (CRs) and Transfer Factors (TFs). The results are compared with two sets of criteria - Screening Criteria and Acceptance Criteria.

For the crystalline site environment, biota dose rates for all assessed scenarios except one are below Screening Criteria. In the one exception, potential dose rates to the Mink were calculated to exceed the Screening Criterion, but remained below the Acceptance Criterion, for the unlikely All Containers Fail Disruptive Scenario. Nevertheless, given the likelihood of all containers failing simultaneously and given that the Acceptance Criterion is not exceeded, the assessment concludes that exposure of Mink is not likely to cause any detrimental effects. The assessment further concludes that exposures to all other non-human biota in the crystalline rock environment are of no radiological concern.

In the sedimentary site environment, biota dose rates are all well below Screening Criteria. Therefore, the assessment concludes that exposures to non-human biota in the sedimentary rock environment are of no radiological concern.

These conclusions are drawn for hypothetical sites, and would need to be repeated for any real candidate site. However these results illustrate the methodology, provide information on the nature and importance of the various pathways, and are consistent with prior conclusions that an appropriately sited deep geologic repository should have no long-term detrimental impact on biota populations around the site.

ABSTRACT

Title: **Non-Radiological Interim Acceptance Criteria for the Protection of Persons and the Environment**
Report No.: **NWMO-TR-2015-03**
Author(s): Chantal Medri
Company: Nuclear Waste Management Organization
Date: January 2015

Abstract
The purpose of this report is to present interim acceptance criteria for the protection of persons and the environment from non-radiological releases (i.e., potentially hazardous chemical elements) from a used fuel deep geological repository. The criteria are based on Canadian Federal and Provincial guidelines and publications, supplemented as required by internationally developed guidelines. Criteria are provided for five environmental media: surface water, groundwater, soil, sediment and air. The criteria are cautiously realistic (i.e., they ensure the protection of persons and the environment without being excessively conservative).

ABSTRACT

Title: **Human Intrusion Model for the Mark II Container in Crystalline and Sedimentary Rock Environments: HIMv2.1**
Report No.: **NWMO-TR-2015-04**
Author(s): Chantal Medri
Company: Nuclear Waste Management Organization
Date: February 2015

Abstract
The Human Intrusion Model for the Mark II Container in Crystalline and Sedimentary Rock Environments (HIMv2.1) is a model for the assessment of the dose consequences from inadvertent human intrusion into a deep geological repository for used nuclear fuel. It is intended for calculating human dose consequences at the surface as a result of a borehole intercepting a Mark II used fuel container in a repository and bringing used fuel debris to the surface.

This report documents the basis for HIMv2.1, which was implemented on the AMBER software platform. It includes the model equations and software documentation. HIMv2.1 calculates the dose consequences to members of two exposure groups:

- A drill crew handling core debris and from contaminated drill slurry (exposure from inhalation, ingestion, groundshine and external irradiation); and
- Residents living in a house on contaminated soil (exposure from groundshine, inhalation, soil and plant ingestion).

Dose consequences are evaluated for a scenario where the used fuel hazard is recognized and the site is completely remediated, and for a scenario where the used fuel hazard is not recognized and the site is not remediated. The dose consequences for the scenario where the fuel hazard is recognized are also evaluated for a higher used fuel burnup.

For the scenario where the fuel hazard is recognized, the estimated peak doses are 90 mSv for the drill crew and 0 mSv for the resident (since the site is assumed to be fully remediated). The estimated peak dose to the drill crew in this scenario for fuel with a higher burnup is 110 mSv. For the scenario where the used fuel hazard is not recognized, the estimated peak doses are 590 mSv per intrusion event for the drill crew and 580 mSv per year for the resident.

The probability of exposure is not estimated in this report. However, the probability of exposure for all scenarios would be small, and even more so for the resident since several very conservative assumptions are embedded in the stylization of the scenario (e.g., the resident is assumed to immediately start growing a garden in the contaminated soil).

ABSTRACT

Title: **Thermal Modelling of a Mark II Container**
Report No.: **NWMO-TR-2015-06**
Author(s): Ruiping Guo
Company: Nuclear Waste Management Organization
Date: April 2015

Abstract
This technical report describes the analysis methods, assumptions and results obtained in calculations performed to assess fuel temperatures inside a Mark II container, which holds 48 used fuel bundles, assuming the fuel bundles have a decay period of 30 years with a discharge burnup of 220 MWh/(kgU). A variety of external boundary conditions is considered:

- Mark II container in air,
- Mark II container inside the buffer box in air,
- Mark II container inside the buffer box in the backfilled sedimentary rock repository, and
- Mark II container inside the buffer box in the backfilled crystalline rock repository.

The effect of filling the container with fuel of mixed age (10 years and 30 years) is also studied.

Sensitivity cases investigate the importance of the following:

- dividing the physical heat transfer systems into different levels of models,
- the small space between the container and the bentonite material in the buffer box,
- connections between bundle tubes and the inside surface of the container,
- water entering the container via an assumed container defect,
- radiation heat transfer between bundle tubes and between bundle tubes and the inside surface of the container,
- radiation heat transfer between fuel elements and between fuel elements and the inside surface of the bundle tube,
- heat transfer coefficient used for the convective heat transfer from the container surface to air, and
- higher burnup of the used fuel bundles.

All cases assume 37-element fuel bundles; however, the results are also generally applicable to 28-element fuel bundles.

The overall conclusion is that the maximum fuel temperature for the fuel with a burnup of 220 MWh/(kgU) will be less than 58°C during handling of the container, about 73°C during handling of buffer box during placement, and about 123°C after placement in sedimentary or crystalline rock repository.

ABSTRACT

Title: **Seismic Activity in the Northern Ontario Portion of the Canadian Shield: Annual Progress Report for the Period January 01 – December 31, 2013**
Report No.: **NWMO-TR-2015-10**

Author(s): J. Adams[1], J.A. Drysdale[1], S.J. Hayek[1], V. Peci[2], S. Halchuk[1] and P. Street[1]
Company: [1]Canadian Hazards Information Service, Geological Survey of Canada, Natural Resources Canada, Government of Canada
[2]V. Peci under contract

Date: December 2015

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 2013.

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 monitoring program.

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 2013, 70 events were located. Their magnitude ranged from 0.9 m_N to 3.8 m_N. The largest event with a magnitude of 3.8 m_N occurred 66 km north of Chapleau, ON. The most westerly event in the area being studied was a m_N 2.4 event, located 62 km west of Red Lake ON. The pattern of seismicity for 2013 is similar to the seismicity patterns of the previous years, although the regions near Kapuskasing and west of North Bay had no events. The 70 events located in 2013 compares with the 57 events located in 2012, 79 events located in 2011, 118 events in 2010, 82 events in 2009, and 114 events in 2008.

ABSTRACT

Title: **Some Implications of Recycling CANDU Used Fuel in Fast Reactors**
Report No.: **NWMO-TR-2015-11**
Author(s): Mihaela Ion
Company: Nuclear Waste Management Organization
Date: December 2015

Abstract
This report documents a high-level analysis of an advanced nuclear fuel cycle where the transuranic (TRU) elements from the CANDU used nuclear fuel (i.e., plutonium, neptunium, americium, and curium) are assumed to be burned (transmuted) in a fast reactor. The fast reactor considered in the analysis is based on the advanced burner reactor preliminary design developed at the Argonne National Laboratory, which is based on the 1000 MWth or 380 MWe SuperPRISM (S-PRISM) reactor designed by GE Hitachi Nuclear Energy.

Mass flow calculations are performed to estimate the impact of such a nuclear fuel cycle from a waste management perspective, i.e., in terms of amounts of generated waste, as well as to estimate the time that would be needed to use up all the transuranic elements in the CANDU used fuel. Input data is based on information available in the open literature.

Scenarios consider the deployment of fast reactors only (no further CANDUs) as a method for waste management and for electricity production. Calculations are performed for different core configurations and metal-fuel options with favourable conversion ratios. For a high TRU consumption rate, a very low conversion ratio would be desired in a fast reactor. A reactor with conversion ratios of 0.25, 0.5 or 0.75 is used to estimate the amount of waste resulting from the overall nuclear fuel cycle. The analysis focuses on the transuranic content as an aggregate, and does not specifically focus on the isotopic content.

Assuming that burner fast reactors and advanced reprocessing and fuel fabrication are practical, then the results indicate that the substantive burnup of the TRUs in CANDU used fuel would require roughly similar numbers of new power blocks of PRISM-type fast reactors (one power block is two 380-MWe S-PRISMs) as the original CANDU reactors. In essence, adopting FRs to burn TRUs is as much an electricity production strategy as a waste management strategy.

With respect to waste management, the mass balance presented in this analysis indicates that the reduction in mass of TRUs for disposal would be accompanied by a larger increase in the mass of fission products requiring long-term management. There is comparatively little reduction in the total amount of uranium that needs to be managed. Also, a relatively significant amount of TRU would still be in the FR cores, which would need to be managed at the end of the operating life of the fast reactors.

Note that this analysis provides an overall mass balance perspective, but does not comment on the practicality of these fast reactor related technologies, the deployment of fast reactors, the specific isotopic and reactor physics implications of these fuel cycles, nor the implications of the hazard of the different final waste products.

ABSTRACT

Title: **MIN3P-THCm Code Enhancements for Reactive Transport Modelling in Low Permeability Media**
Report No.: **NWMO-TR-2015-12**
Author(s): Mingliang Xie[1], Pejman Rasouli[1], K. Ulrich Mayer[1] and Kerry T. B. MacQuarrie[2]
Company: [1]Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia
[2]Department of Civil Engineering, University of New Brunswick
Date: July 2015

Abstract

The reactive transport code MIN3P-THCm was enhanced by strengthening its simulation capabilities for geochemical processes in low permeability porous media in which transport is diffusion-controlled. Code enhancements include a multisite ion exchange (MIE) model, a multicomponent diffusion (MCD) model, and a hybrid multicomponent diffusion (hMCD) model. Simulation capabilities were further extended by implementing domain discretization in radial coordinates, in addition to standard Cartesian coordinates. The code enhancements are useful for simulating reactive transport in engineered barrier systems and in low permeability host rock considered for deep geological repositories. This report documents the theoretical background, the governing equations, and the numerical implementation for these new ion exchange and diffusion modules. In addition, relevant sections of the updated user guide are described and verification examples for evaluation of the simulation capabilities are provided.

ABSTRACT

Title: **T2GGM Version 3.2: Gas Generation and Transport Code**
Report No.: **NWMO-TR-2015-13**
Author(s): P. Suckling[1], J. Avis[2], N. Calder[2], O. Nasir[2], P. Humphreys[3], F. King[4], R. Walsh[2]
Company: [1]Quintessa Ltd., [2]Geofirma Engineering Ltd., [3]University of Huddersfield, [4]Integrity Corrosion Consulting Ltd.
Date: November 2015

Abstract
T2GGM is a software package that can be used to analyze the generation and transport of gases and groundwater in a deep geologic repository. The current version is Version 3.2. It includes gas generation from low and intermediate level waste, and gas generation from the corrosion of used fuel containers under relevant conditions.

This report provides a reference manual for the T2GGM software. It includes the theory for the gas generation model, the user guide with descriptions of the software inputs and outputs, a summary of the verification that the software has undergone and software validation.

T2GGM includes the following capabilities:

- Corrosion product and hydrogen gas generation from corrosion of steels and other alloys under aerobic and anaerobic conditions;
- CO_2 and CH_4 gas generation from degradation of organic materials under aerobic and anaerobic conditions;
- H_2 gas reactions, including methanogenesis with CO_2;
- Biomass generation, decay and recycling;
- Exchange of gas and water between the repository and the surrounding geosphere; and
- Two-phase flow of water and gas within the geosphere.

Key results include the gas pressure and water saturation levels within a repository, as well as flow rates of water and gas within the geosphere. T2GGM does not include radionuclide transport and decay.

T2GGM is comprised of two coupled models: a Gas Generation Model (GGM) used to model the generation of gas within a repository due to corrosion and microbial degradation of the various materials present, and a TOUGH2 model for gas-water transport from the repository through the geosphere.

ABSTRACT

Title: **Long-Term Stability Analysis of APM Conceptual Design in Sedimentary and Crystalline Rock Settings**
Report No.: **NWMO-TR-2015-15**
Author(s): Zorica Radakovic-Guzina, Azadeh Riahi and Branko Damjanac
Company: Itasca Consultant Group, Inc.
Date: December 2015

Abstract

The long-term safety and performance of a Deep Geological Repository for used nuclear fuel will rely, in part, on the integrity of the geosphere barrier enclosing the repository. The purpose of this report is to present an illustrative case study intent on providing a bounding thermal-mechanical-hydraulic estimate of repository and geosphere response and evolution during excavation, operations and post-closure phases. The analyses consider the Mark II (48 bundle) canister design and repository configuration in crystalline and sedimentary rock settings at a nominal depth of 500 m below ground surface. On a timeframe of 1 million years (1Ma), a period relevant to the demonstration of repository safety, the influence of time dependent material properties and varied repository loading conditions are simulated. These include long-term rock mass strength degradation, thermal loading generated by canister heat flux, glacial ice-sheet advance and retreat, rare and extremely strong earthquake ground motions, internal repository gas pressure generated by canister corrosion, and transient hydraulic formation pressures. The analysis conducted is focused at the scale of the canister placement rooms and repository panels. Results provide time series estimates of overall repository stability during 1Ma that, among other factors, provide quantitative estimates of rock mass deformation and damage, evolution of the Excavation Damage Zone (EDZ), and the hydraulic and mechanical loading of a used fuel canister.

In order to conduct the analyses a number of assumptions were applied to explore and test notions of geosphere and repository stability and resilience to future loading. These included:

1) Hydraulic Formation Pressures: A hydrostatic formation porewater pressure of 5 MPa was assumed for the repository at 500 m depth;

2) Long-term Rock Mass Strength: Time dependent rock mass strength degradation was simulated with the long-term rock mass strength set to 40% of Unconfined Compressive Strength (UCS). This long-term rock mass strength is equivalent to the crack initiation stress;

3) Temperature Evolution: The emplacement room geometry and layout is designed to ensure the maximum used fuel canister surface temperature remains less than 100°C;

4) Glaciation: Transient glacial ice-sheet history and loading were explicitly considered with maximum ice-sheet thicknesses approaching 3 km;

5) Earthquakes: Rare and strong ground motions (i.e., 0.5g) associated with long return period (1Ma) earthquakes were simulated;

6) Repository Gas Pressures: Gas generation within the repository as a result of corrosion yields a maximum pressure of 8.3 MPa;

7) Effective Stress Formulation: Effective stress calculations were estimated without considering pore pressure relief in the low porosity rocks;

8) Joint Strength: Pre-existing joints within a crystalline rock mass were assumed to be cohesionless with a relatively low friction angle of 30°; and

9) Thermal Expansivity: Relatively high coefficients of thermal expansion were applied to yield bounding estimates of rock mass damage.

For both sedimentary and crystalline settings rock mass damage will occur as a result of: i) transient changes in in-situ stress magnitude and orientation; ii) thermally-induced stress changes; and iii) time-dependent rock mass strength degradation. It is evident from the analyses that damage is primarily driven by thermally-induced stress changes occurring within approximately 1,000 years of repository closure. Glacial ice-sheet loading and strong earthquake ground motion do not materially influence rock damage. The bounding long-term rock mass strength of 40% UCS does not yield significant damage and, in this case, it is evident that the engineered backfill provides confinement that mitigates spalling, fracture dilation, and likely contributes to slowing the rate of time-dependent strength degradation. Displacements are uniform and relatively small not exceeding 40 mm. During glaciation maximum displacements are estimated not to exceed 12 mm. The EDZ is predicted to extend not more than 1 to 3 meters into the enclosing host rock formation from excavated surfaces. For this illustrative case study, the maximum loading of used fuel canisters for the sedimentary and crystalline scenarios is predicted to be 22.7 and 29.8 MPa, respectively. A detailed explanation of the above findings and unique aspects related to sedimentary and crystalline environs is provided herein.

ABSTRACT

Title: **Surface Boundary Conditions During Long-Term Climate Change**
Report No.: **NWMO-TR-2015-16**
Author(s): Gordan Stuhne and W. R. Peltier
Company: University of Toronto
Date: September 2015

Abstract
The latest version of the University of Toronto Glacial Systems Model (UofTGSM) was employed in the development of data sets describing the evolution of surface boundary conditions above a potential spent fuel repository over the course of a 122.5 kyr cycle of glaciation. The new data sets build increased confidence upon the previous UofT GSM generated data sets that Peltier (2006) supplied for this purpose. The components of the UofT GSM have been updated to a framework reflecting the current state-of-the-art, and a new strategy has been adopted to preserve consistency with observations independently of detailed assumptions about ice-sheet dynamics. A mass-balance adjustment is employed to nudge the ice-thickness solution towards the observationally well-validated ICE-6G_C reconstruction, and dynamical variability can be analyzed in the context of ensembles with different exponential relaxation time-scales. This approach is used to diagnose 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. Beyond reflecting significant numerical advances that enabled the new UofT GSM to better represent basal processes, ice-shelves, temperate ice-water mixtures and other physics, the new results benefit from the many new measurements that constrained ICE-6G_C (and therefore, indirectly, the nudged paleoclimate simulations). Nudging offers a more practical approach to leading-order data assimilation and error estimation than Bayesian calibration, which was employed in Peltier (2006), and which will continue to be of use in more detailed explorations of observationally constrained model parameter spaces. Rather than consisting of discrete time-series at the sites of hypothetical spent-fuel repositories, the new dataset also includes time-varying two-dimensional geographic distributions covering all of Canada.

ABSTRACT

Title: **Assessing Radiological Dose to Members of the Public and Workers during UFTP Transportation**
Report No.: **NWMO-TR-2015-17**
Author(s): U. Stahmer
Company: NWMO
Date: September 2015

ABSTRACT

In 2012, the NWMO prepared an assessment that estimated radiological dose to members of the public resulting from the transport of used nuclear fuel in the Used Fuel Transportation Package (UFTP) (Batters et al., 2012). The dose estimates were built around generic, internationally available exposure time, distance and frequency assumptions.

In 2014, work was initiated to refine these assumptions and to frame them in a Canadian context. Carleton University was contracted by the NWMO to assess exposure times, distances and frequencies between the members of the public and a passing UFTP along a hypothetical transport route. The data collected by Carleton reflects a realistic, current Canadian perspective on the time, distance and frequency relationships between members of the public and a UFTP shipment.

This assessment uses the data collected by Carleton to re-examine and update the generic public dose estimates prepared in 2012 and provides an estimate of public dose within a Canadian context. Furthermore, this report summarises radiological doses to workers involved in the transport of used nuclear fuel in Canada, assessed in Stahmer (2014).

Public Dose Assessment

Using dose rates established in Batters et al. (2012) and the time, distance and frequency data collected by Carleton, the public dose assessment was updated. Activities placing members of the public in the proximity of a UFTP shipment were identified and grouped into the following eight categories:

1. Resident – a member of the public living along a UFTP transport route;
2. Pedestrian – a member of the public present at the roadside of a passing UFTP shipment;
3. Hitchhiker – a member of the public on the roadside soliciting a ride from passing vehicles as a UFTP shipment passes by;
4. Roadside Worker – a member of the public working along the roadside as a UFTP shipment passes by;
5. Cyclist – a member of the public cycling along the roadside as a UFTP shipment passes by;
6. Vehicle Occupant – a member of the public in a vehicle sharing the road with a UFTP shipment;
7. Traveler at a Stop – a member of the public present near a UFTP shipment during an en-route stop; and

8. Commercial Driver at a Refuelling Stop – a member of the public refuelling their vehicle in the proximity of a UFTP shipment also being refueled.

Exposure time is determined as a factor of transport speed of the UFTP shipment. Exposure distance is determined by the relative position between a member of the public and a UFTP shipment. As both exposure time and distance are related to the road type the shipment is travelling along, transport along three road types (urban, highway, and controlled access highway) were also considered.

Radiological doses to members of the public were estimated to range between approximately 0.0000013 to 0.00054 mSv per year with certain roadway workers potentially receiving the highest dose. Findings for the eight categories of members of the public are tabulated in Figure S-1 below. All doses were calculated to be orders of magnitude below the regulatory dose limit of 1 mSv per year for a member of the public. The member of the public receiving the highest annual dose was determined to be a traffic control person (roadside worker), who may receive an annual dose 1900 times less than the public dose limit or a dose equivalent to that received during 8 minutes of flight in a jet airplane.

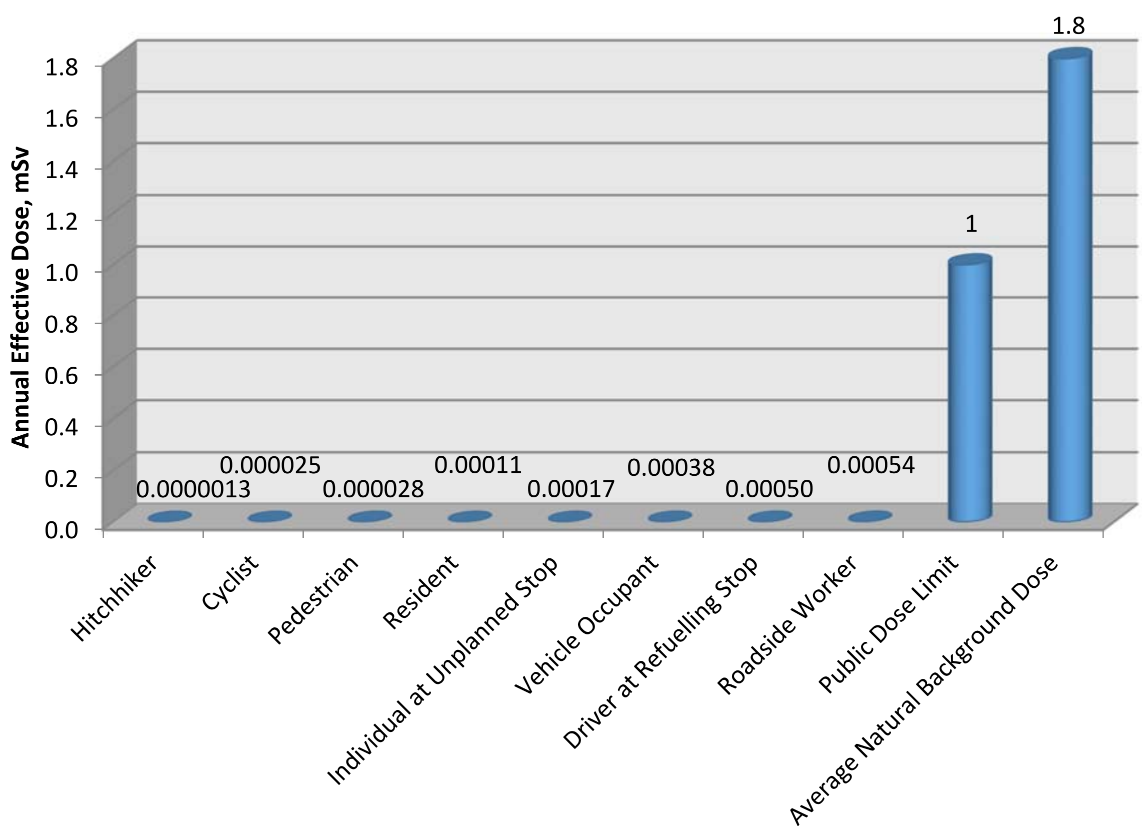

Figure S-1: Comparison of Public Doses

Worker Dose Assessment

In 2014, the NWMO prepared a companion report to the 2012 Generic Public Dose Assessment which assessed the radiological dose to workers associated with the transportation of used nuclear fuel (Stahmer, 2014). The results from the worker dose assessment are included in this report for completeness.

The report (Stahmer, 2014) focuses on activities performed by workers from the time a used nuclear fuel shipment departs from the reactor site where the fuel is currently stored until its arrival at the repository site. Occupational doses were assessed to be within a range of approximately 0.012 to 0.35 mSv per year with members of the transport crew receiving the highest dose; approximately 1/3rd of the public dose limit or equivalent to the dose received during 88½ hours of flight in a jet airplane. The transport crew would receive only about 15% of the dose a typical flight crew receives annually (Shea and Smart, 2001).

Since calculated doses remained below the regulatory dose limit of 1 mSv per year for a member of the public, the assessment concludes that transportation workers would not need to be designated as Nuclear Energy Workers (NEWs)[1] (Stahmer, 2014). However, dose monitoring of occupational activities for the transport crew should be evaluated as the radiation protection program is developed, prior to the operational start-up of the used fuel transportation program. Findings for different transportation worker categories are tabulated in Figure S-2.

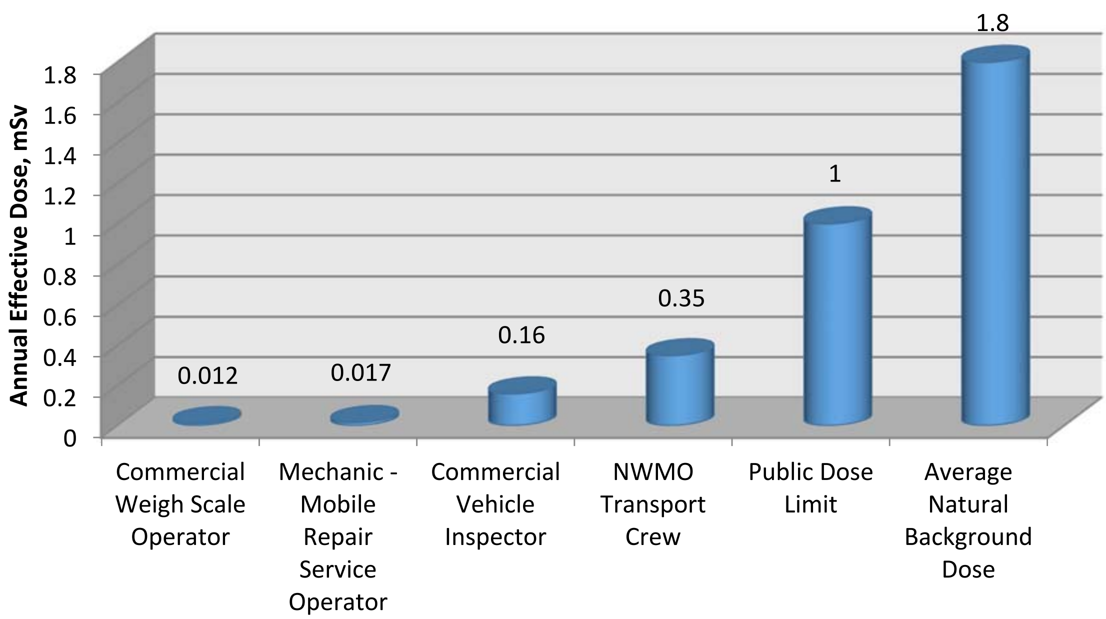

Figure S-2: Comparison of Worker Doses

As the location of the Adaptive Phased Management (APM) repository site is currently unknown, program specific calculations and risk assessments are still premature. The intent of this assessment is to provide a starting point to address concerns about the safety of the transportation system in a transparent manner.

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[1] A Nuclear Energy Worker (NEW) is a worker who is required to perform duties that may result in a dose of radiation that is greater than the prescribed limit for the general public (GoC, 1997). See the Acronyms and Definitions section.

ABSTRACT

Title: **An Update to the Canadian Shield Stress Database**
Report No.: **NWMO-TR-2015-18**
Author(s): Salina Yong and Sean Maloney
Company: MIRARCO
Date: September 2015

Abstract

This report provides an update of the 2005 state of ground stress report for the Ontario portion of the Canadian Shield. A database of 304 stress measurements has been assembled that includes 75 new measurements since 2005. The database covers a range of depths between 12 and 2,552 m below ground surface with measurement data obtained largely from operating mines in Ontario. A data screening process was followed that involved 5 acceptance criteria to assess quality and reduce uncertainty when establishing representative ground stress state equations. As a result of the data screening, the database supporting the analysis in this study was reduced to 199 entries.

Consistent with past studies, the state of ground stress in Shield terrain is sub-divided into 3 Zones: i) the stress-relaxed zone (Domain 1; 0-300m); ii) the transitional zone (Domain 2; 300 – 600 m); iii) the undisturbed zone (Domain 3; 600-1500m). The best-fit relationships are developed for Domains 1 and 3 as evidence suggests the interpretations are robust and less sensitive to site specific conditions. Variability and uncertainty is highest in transitional stress Domain 2, which reveals a strong dependency on the local geologic setting. As recommended in 2005, stresses in Domain 2 can be assumed to increase linearly between Domains 1 and 3 for preliminary modelling and sub-surface design purposes.

While this review has provided insight on the stress state within in the crystalline rocks of the Canadian Shield, direct measurements of ground stress magnitudes and orientations are required to provide site-specific estimates that further constrain stress state and reduce uncertainty.

ABSTRACT

Title: **Nuclear Fuel Waste Projections in Canada – 2015 Update**
Report No.: **NWMO-TR-2015-19**
Author(s): M. Garamszeghy
Company: Nuclear Waste Management Organization
Date: December 2015

Abstract
This summarizes the existing inventory of used nuclear fuel wastes in Canada as of June 30, 2015 and forecasts the potential future arisings from the existing reactor fleet as well as from proposed new-build reactors. The report focuses on power reactors, but also includes prototype, demonstration and research reactor fuel wastes held by AECL which are included in the NWMO mandate.

As of June 30, 2015, a total of approximately 2.6 million used CANDU fuel bundles (approx. 52,000 tonnes of heavy metal (t-HM)) were in storage at the reactor sites, an increase of approximately 88,000 bundles from the 2014 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 3.4 to 5.2 million used CANDU fuel bundles (approx. 69,000 t-HM to 103,000 t-HM), depending upon decisions to refurbish current reactors. The lower end is based on an average of 25 effective full power years (EFPY) of operation for each reactor (i.e. no 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. This is unchanged from the 2014 report.

Based on currently announced refurbishment and life extension plans for the existing nuclear reactor fleet in Canada, the current reference scenario projects a total of 4.4 million bundles. For design and safety assessment purposes, the NWMO has assumed a reference used fuel inventory of 4.6 million CANDU fuel bundles from the existing reactor fleet.

Used fuel produced by potential new-build reactors will depend on the size and type of reactor and number of units deployed. New-build plans are at various stages of development and the decisions about whether to proceed with individual projects, reactor technology and number of units have not yet been made. If all of the units where 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 2014 report.

When decisions on reactor refurbishment, new nuclear build and/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: **Chlorine and Bromine Isotopic Analyses of Groundwaters: DGR-3 and DGR-4**
Report No.: **NWMO-TR-2015-20**
Author(s): Yinze Wang and Shaun Frape
Company: Department of Earth and Environmental Sciences, University of Waterloo
Date: November 2015

Abstract

This report describes $\delta^{37}Cl$ and $\delta^{81}Br$ isotopic analyses for groundwaters from confined saline aquifers of Silurian and Cambrian age on the eastern flank of the Michigan Basin within the Huron Domain. In total, six groundwater samples were obtained during opportunistic sampling of the carbonate Salina A1 and Guelph formations and over-pressured Cambrian sandstone during the drilling of deep boreholes DGR-3 and DGR-4 at the Bruce nuclear site, near Kincardine, Ontario. The stable isotopes of Cl and Br, in conjunction with their geochemical parameters, are examined to ascertain the origin of salts and fluids containing these elements, as well as to identify processes that cause isotopic fractionation. Paleohydrogeologic information in the context of regional scale groundwater system dynamics and solute migration is provided by comparing the groundwater halide geochemical and isotopic values determined with other samples from equivalent geologic formations.

Study results reveal that the sampled groundwaters have isotopic and geochemical signatures similar to formation fluids from the same geological units collected in the Niagara tectonic block, southeast of the Algonquin arch. The Salina A1 samples appear to have been altered by halite dissolution and mixing with cold climate recharge. The Salina A1 and Guelph formation groundwaters are both isotopically depleted in $\delta^{81}Br$. This is similar to other regional groundwaters that are described as having been sourced within the Michigan Basin. In contrast, the Cambrian groundwaters show enriched $\delta^{81}Br$ and $\delta^{37}Cl$ isotopic signatures. These signatures are similar to those found elsewhere in the Cambrian as it occurs in the Appalachian Basin to the east and south. The halide isotopic signatures of the Cambrian groundwaters suggest that these fluids may be very old as their isotopic compositions have been maintained since emplacement during regional basinal fluid events occurring in the early Paleozoic.

ABSTRACT

Title:	**Seismic Activity in the Northern Ontario Portion of the Canadian Shield: Annual Progress Report for the Period January 01 – December 31, 2014**
Report No.:	**NWMO-TR-2015-21**
Author(s):	J. Adams[1], V. Peci[2], J.A. Drysdale[1], S. Halchuk[1] and P. Street[1]
Company:	[1]Canadian Hazards Information Service, Geological Survey of Canada, Natural Resources Canada, Government of Canada [2]V. Peci under contract
Date:	December 2015

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 2014.

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 monitoring program.

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 2014, 36 earthquakes were located. Their magnitude ranged from 1.1 m_N to 3.0 m_N. The largest event, with a magnitude of 3.0 m_N, occurred 190 km northwest of Victor Mine, ON, while the second largest event 2.8 m_N, was located in the James Bay region 95 km north from Moosonee, ON. The 36 events located in 2014 compares with 70 events located in 2013, 57 events in 2012, 79 events in 2011, 118 events in 2010, 82 events in 2009, and 114 events in 2008.

ABSTRACT

Title: **Preliminary Hazard Assessment of Waste from an Advanced Fuel Cycle**
Report No.: **NWMO-TR-2015-22**
Author(s): Mark Gobien
Company: Nuclear Waste Management Organization
Date: December 2015

Abstract

This report documents a high-level analysis of the hazard posed by wastes generated by an advanced nuclear fuel cycle where transuranic (TRU) elements from CANDU used nuclear fuel (i.e., plutonium, neptunium, americium, and curium) are assumed to be transmuted (burned) in a fast reactor. The primary waste streams consist of fission products intentionally removed during the reprocessing process, U and TRU that enter the wastes due to inefficiencies in the reprocessing and fuel fabrication processing, and the surplus U from the fabrication of new fast reactor fuel from spent CANDU fuel. The inventories in the waste stream from a fast reactor based fuel cycle were previously estimated using mass balance calculations.

This report considers pyroprocessing as the reference method used to reprocess spent CANDU and spent fast reactor fuel. The waste salt from pyroprocessing is assumed to be converted into a stable ceramic-glass wasteform. The properties and radionuclide loading of the fast reactor wasteform used to encapsulate waste stream radionuclides extracted during reprocessing are described based on available literature.

With respect to the hazard of the fast reactor wasteform, the wasteform radioactivity, radiotoxicity, thermal power, and unshielded dose rate are estimated and compared to an equivalent amount of spent CANDU fuel. This analysis shows that the fast reactor wasteform from reprocessing and spent CANDU fuel are broadly similar on a per kg of wasteform basis. The fast reactor wasteform is more hazardous in the short term, and the spent CANDU fuel is more hazardous in the long term.

Finally, the long-term safety of the fast reactor waste is considered. Two options are considered - placement in a deep geological repository, and placement after 300-years decay in a near-surface landfill. This analysis shows that the dose consequences as a result of surface disposal of reprocessing wastes would be high over long periods of time. That is, even after several hundred years of decay, the fast reactor wasteform is a long-lived nuclear waste which would require appropriate management such as a deep geological repository.

ABSTRACT

Title: **Parallelization of the Reactive Transport Code MIN3P-THCm**
Report No.: **NWMO-TR-2015-23**
Author(s): Danyang Su[1], K. Ulrich Mayer[1] and Kerry T.B. MacQuarrie[2]
Company: [1]Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia
[2]Department of Civil Engineering, University of New Brunswick
Date: October 2015

Abstract
Reactive transport modelling can be time consuming and memory-intensive, especially for large-scale, long-term simulations with a large number of chemical components and interactions. The objective of this research was to develop a parallel version of MIN3P-THCm, a general purpose multicomponent reactive transport code for variably saturated porous media. The resulting program, entitled ParMIN3P-THCm, is able to deal with the significant computational burden of reactive transport simulations involving large spatial scales and long time frames and can be run efficiently on machines ranging from desktop PCs, shared-memory workstations, to distributed-memory supercomputers.

Parallelization of MIN3P-THCm (ParMIN3P-THCm) was achieved through the domain decomposition method based on PETSc (Portable Extensible Toolkit for Scientific Computation) libraries. PETSc is also used as the parallel solver package, and for data structure and message communication. A hybrid MPI and OpenMP parallel programming approach is implemented in the code to take advantage of leadership-class supercomputers that combine both shared memory and distributed memory architectures. Features of the code include a modular input file, parallel configuration file, and parallel I/O, with potential expansibility to incorporate additional features in the near feature such as high-performance I/O using parallel HDF5, as well as parallel multigrid and unstructured grid methods. ParMIN3P-THCm has been developed from the ground up for parallel scalability and has been run using up to 768 processors with problem sizes up to 100 million unknowns. The code has demonstrated excellent speedup for reactive transport simulation problems using 8 processors on a local shared-memory workstation, 128 processors on the WestGrid supercomputer using MPI parallelization and 768 processors on the WestGrid supercomputer using hybrid MPI-OpenMP parallelization. The code has shown strong scalability in modelling large-scale reactive transport problems.

ABSTRACT

Title: **Fluid Inclusion Study of Drill Core and Outcrop Samples from the Bruce Nuclear Site, Southern Ontario**
Report No.: **NWMO-TR-2015-24**
Author(s): L. W. Diamond, L. Aschwanden, R. Caldas
Company: Rock-Water Interaction Group, Institute of Geological Sciences, University of Bern, Switzerland
Date: December 2015

Abstract

Fluid inclusions were investigated in carbonate vugs and veinlets in fifteen drill core samples from beneath the Bruce nuclear site, including samples from Cambrian, Ordovician and Devonian formations. Six samples of calcite veins from an outcrop of the Lucas Formation were also investigated. The inclusions were analysed petrographically in visible and UV light and by laser Raman spectroscopy and crushing-stage experiments. The inclusions in calcite proved difficult to analyse, owing to the widely known phenomenon of stretching upon heating. Accordingly, the analytical workflow included a procedure to sort valid data from artefacts. The interpretation of the results involved thermodynamic modelling to estimate salinities and trapping temperatures.

The fluid inclusion record is highly consistent between the 15 samples, supporting the idea that geological features within the DGR site are predictable from the acquired evidence. The results show that the deep Cambrian to Mid-Ordovician vugs and veins share the same history of fluid evolution, and are thus genetically related, whereas the veinlets in the shallow Devonian Lucas Formation formed from very different fluids.

In the Cambrian to Mid-Ordovician carbonates, five "paleofluids" have been recognized which are similar to diagenetic fluids reported in the same units in the regional literature. Each paleofluid precipitated minerals or was present during microfracturing in the vugs and veins. Paleofluid 1 was a mixture of halite-saturated brine + free methane±CO_2 gas that precipitated saddle- and rhombic-habit dolomite. The saddle dolomites precipitated at 122–128 °C. Paleofluid 2, a similar halite-saturated, two-phase mixture (brine + free methane gas), infiltrated the vugs and veins in pulses at temperatures between 42 and 85 °C. Paleofluid 3 was a halite-saturated brine without an accompanying gas phase. It healed microfractures in the previously precipitated minerals after infiltrating in pulses at temperatures between 71 and 120 °C. Paleofluid 4 was a simple halite-undersaturated brine, without free gas, that entered the sediments at some temperature below 70 °C. Paleofluid 5 consisted of light petroleum oil accompanied by free methane gas that was trapped in microfractures at 50–60 °C. No indication has been found in the Cambrian to Mid-Ordovician samples for a fluid that could have originated by influx of glacial melt-water.

The Devonian Lucas limestone contains a record of three additional paleofluids. Paleofluid 6 was a low-salinity aqueous solution accompanied by free methane gas, which precipitated calcite and minor ankerite in veinlets at ~60 °C. Paleofluid 7 was a slightly diluted version of Paleofluid 6 but without free gas in the aqueous solution. Paleofluid 8 consisted of light petroleum oil accompanied by free methane gas. Overall, the low salinity fluids in the Devonian Lucas Formation contrast strongly with the brines in the underlying Cambrian to Mid-Ordovician rocks, ruling out a common fluid origin.

ABSTRACT

Title: **Validation of MoFrac 2.0 using the Äspö Dataset**
Report No.: **NWMO-TR-2015-25**
Author(s): Subash Bastola, Lorrie Fava, Ming Cai
Company: MIRARCO Mining Innovation
Date: December 2015

Abstract

The MoFrac software tool implements the methodology developed by Mohan Srivastava for modelling three-dimensional fracture networks. The study described in this report aims to validate the MoFrac 2.0 software. The validation focuses on the following features of the generated discrete fracture networks (DFNs): 1) fracture shape and undulation, 2) fracture orientation, 3) fracture intensity, 4) fracture traces, 5) fracture truncation rules, 6) fracture joining, and 7) regions. Detailed underground mapping data from the Äspö site near Oskarshamn, Sweden were made available for the purposes of this study. A section of the Äspö tunnel system called TAS08 was selected for generating a dataset including fracture traces, orientation, length, and intensity data, referred to in this document as the Äspö base condition dataset. The validation study also makes use of artificial datasets, referred to as ‘forced conditions’ in the document, where extreme values are assigned for certain DFN parameters in order to observe the effect on generated DFNs. In addition, a synthetic dataset known as Hyposite is also used for the trace validation exercise. With a few noted limitations, MoFrac 2.0 produced DFNs that conformed to the input parameters. Accordingly, MoFrac 2.0 can be used to generate DFN models incorporating field mapping data from underground excavations

ABSTRACT

Title: **Long-Term Stability Analysis of APM Conceptual Repository Design in Sedimentary and Crystalline Rock Settings**
Report No.: **NWMO-TR-2015-27**
Author(s): Zorica Radakovic-Guzina, Azadeh Riahi and Branko Damjanac
Company: Itasca Consultant Group, Inc.
Date: December 2015

Abstract

The long-term safety and performance of a Deep Geological Repository for used nuclear fuel will rely, in part, on the integrity of the geosphere barrier enclosing the repository. The purpose of this report is to present an illustrative case study intent on providing a bounding thermal-mechanical-hydraulic estimate of repository and geosphere response and evolution during excavation, operations and post-closure phases. The analyses consider the Mark II (48 bundle) canister design and repository configuration in crystalline and sedimentary rock settings at a nominal depth of 500 m below ground surface. On a timeframe of 1 million years (1Ma), a period relevant to the demonstration of repository safety, the influence of time dependent material properties and varied repository loading conditions are simulated. These include long-term rock mass strength degradation, thermal loading generated by canister heat flux, glacial ice-sheet advance and retreat, rare and extremely strong earthquake ground motions, internal repository gas pressure generated by canister corrosion, and transient hydraulic formation pressures. The analysis conducted is focused at the scale of the canister placement rooms and repository panels. Results provide time series estimates of overall repository stability during 1Ma that, among other factors, provide quantitative estimates of rock mass deformation and damage, evolution of the Excavation Damage Zone (EDZ), and the hydraulic and mechanical loading of a used fuel canister.

In order to conduct the analyses a number of assumptions were applied to explore and test notions of geosphere and repository stability and resilience to future loading. These included:

1) Hydraulic Formation Pressures: A hydrostatic formation porewater pressure of 5 MPa was assumed for the repository at 500 m depth;
2) Long-term Rock Mass Strength: Time dependent rock mass strength degradation was simulated with the long-term rock mass strength set to 40% of Unconfined Compressive Strength (UCS). This long-term rock mass strength is equivalent to the crack initiation stress;
3) Temperature Evolution: The emplacement room geometry and layout is designed to ensure the maximum used fuel canister surface temperature remains less than 100°C;
4) Glaciation: Transient glacial ice-sheet history and loading were explicitly considered with maximum ice-sheet thicknesses approaching 3 km;

5) Earthquakes: Rare and strong ground motions (i.e., 0.5g) associated with long return period (1Ma) earthquakes were simulated;

6) Repository Gas Pressures: Gas generation within the repository as a result of corrosion yields a maximum pressure of 8.3 MPa;

7) Effective Stress Formulation: Effective stress calculations were estimated without considering pore pressure relief in the low porosity rocks;

8) Joint Strength: Pre-existing joints within a crystalline rock mass were assumed to be cohesionless with a relatively low friction angle of 30°; and

9) Thermal Expansivity: Relatively high coefficients of thermal expansion were applied to yield bounding estimates of rock mass damage.

For both sedimentary and crystalline settings rock mass damage will occur as a result of: i) transient changes in in-situ stress magnitude and orientation; ii) thermally-induced stress changes; and iii) time-dependent rock mass strength degradation. It is evident from the analyses that damage is primarily driven by thermally-induced stress changes occurring within approximately 1,000 years of repository closure. Glacial ice-sheet loading and strong earthquake ground motion do not materially influence rock damage. The bounding long-term rock mass strength of 40% UCS does not yield significant damage and, in this case, it is evident that the engineered backfill provides confinement that mitigates spalling, fracture dilation, and likely contributes to slowing the rate of time-dependent strength degradation. Displacements are uniform and relatively small not exceeding 40 mm. During glaciation maximum displacements are estimated not to exceed 12 mm. The EDZ is predicted to extend not more than 1 to 3 meters into the enclosing host rock formation from excavated surfaces. For this illustrative case study, the maximum loading of used fuel canisters for the sedimentary and crystalline scenarios is predicted to be 22.7 and 29.8 MPa, respectively. A detailed explanation of the above findings and unique aspects related to sedimentary and crystalline environs is provided herein.