Technical Program for Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2021

NWMO-TR-2022-01 July 2022

Nuclear Waste Management Organization (S. Briggs, ed.)

NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

Nuclear Waste Management Organization
22 St. Clair Avenue East, 4th Floor
Toronto, Ontario
M4T 2S3
Canada

Tel: 416-934-9814
Web: www.nwmo.ca

Technical Program for Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2021

NWMO-TR-2022-01

July 2022

Nuclear Waste Management Organization (S. Briggs, ed.)

Document History

Title:	Technical Program for Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2021		
Report Number:	NWMO-TR-2022-01		
Revision:	R000	Date:	July 2022
Nuclear Waste Management Organization			
Authored by:	NWMO (S. Briggs, ed.)		
Reviewed by:	P. Gierszewski		
Approved by:	C. Boyle		

ABSTRACT

Title: **Technical Program for the Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2021**
Report No.: **NWMO-TR-2022-01**
Author(s): NWMO (S. Briggs, ed.)
Company: Nuclear Waste Management Organization
Date: July 2022

Abstract

This report is a summary of activities and progress in 2021 for the Nuclear Waste Management Organization's Technical Program. The primary purpose of the Technical Program is to support the implementation of Adaptive Phased Management (APM), Canada's approach for the long-term management of used nuclear fuel.

The work continued to develop the repository design; to understand the engineered barrier, geological and other processes important to the safety case; and to assess the siting areas.

NWMO continued to participate in international research activities, including projects associated with the Mont Terri Underground Rock Laboratory, the SKB Äspö Hard Rock Laboratory, the ONKALO facility, the Grimsel Test Site, and the OECD (Organisation for Economic Co-operation and Development) Nuclear Energy Agency.

NWMO's technical program supported technical presentations at national and international conferences, issued 10 NWMO technical reports and published 27 journal articles.

TABLE OF CONTENTS

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. This is 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 2007.

The technical objective of the APM approach is a Deep Geological Repository (DGR) that provides long-term isolation and containment, to ensure safety of people and the environment while the radioactivity in the used fuel decays.

The deep geological repository is a multiple-barrier system designed to safely contain and isolate used nuclear fuel over the long term. It will be constructed at a depth of more than 500 metres, depending upon the geology of the site, and consist of a series of tunnels leading to a network of placement rooms where the used nuclear fuel will be contained using a multiple-barrier system. A conceptual design for a DGR is illustrated in Figure 1-1 for a generic rock setting (the design will be varied for actual rock conditions).

The NWMO is presently in the Site Selection phase. No site has been selected to host the DGR. The process for selecting a host community is described 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 a) initial screenings to evaluate the suitability of candidate sites against a list of preliminary screening criteria, using readily available information; b) preliminary assessments to further determine if candidate sites may be suitable for developing a safe used fuel repository; and c) detailed field investigations to confirm suitability of one site.

Initially, 22 communities had expressed interest in the program. By 2021 the number of communities engaged in the site selection process had been narrowed to two, the Wabigoon Lake Ojibway Nation (WLON)-Ignace area and the Saugeen Ojibway Nation (SON)-South Bruce area, based on preliminary assessments of potential geological suitability and potential for the project to contribute to community well-being. The location of these potential sites is shown in Figure 1-2. Reports documenting the site selection process to date are available on the NWMO website (http://www.nwmo.ca/sitingprocess_feasibilitystudies).

The NWMO continues to conduct technical work to support design, site assessment and safety case for a DGR, in parallel with work to engage with and establish a partnership with communities. This report summarizes technical work conducted in 2021. In the near term, this information will support selection of a preferred site, anticipated to be selected in 2023. In the longer term, this will support an impact assessment and licence applications at the selected site. NWMO's overall implementation plan is described in *Implementing Adaptive Phased Management* 2021-2025 (NWMO 2021a).

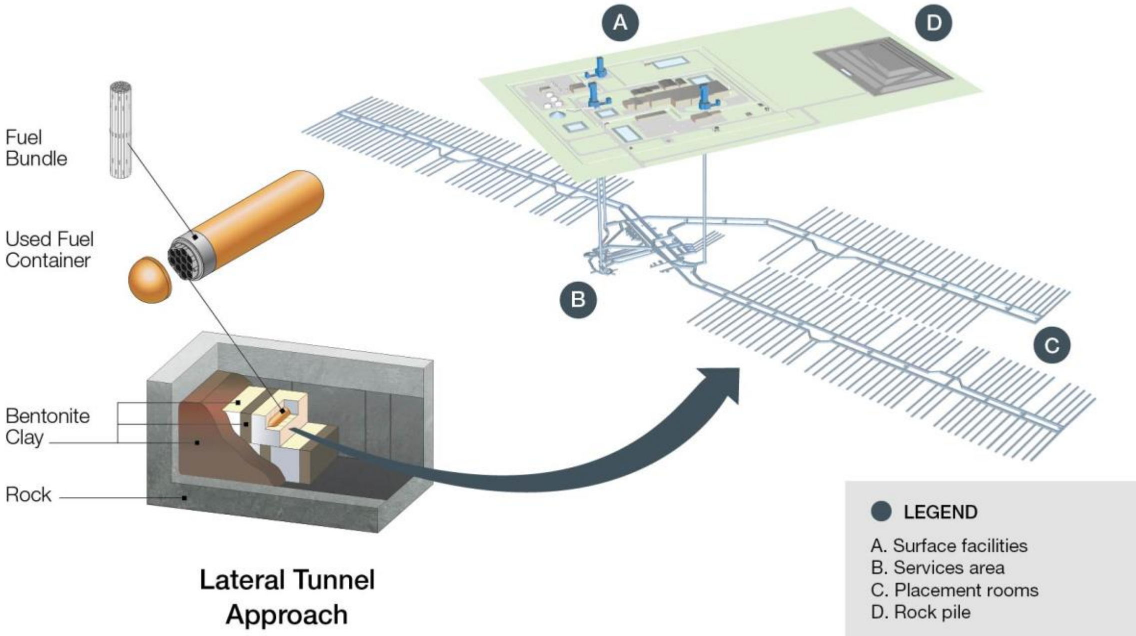


Figure 1-1: Illustration of a Deep Geological Repository Reference Design

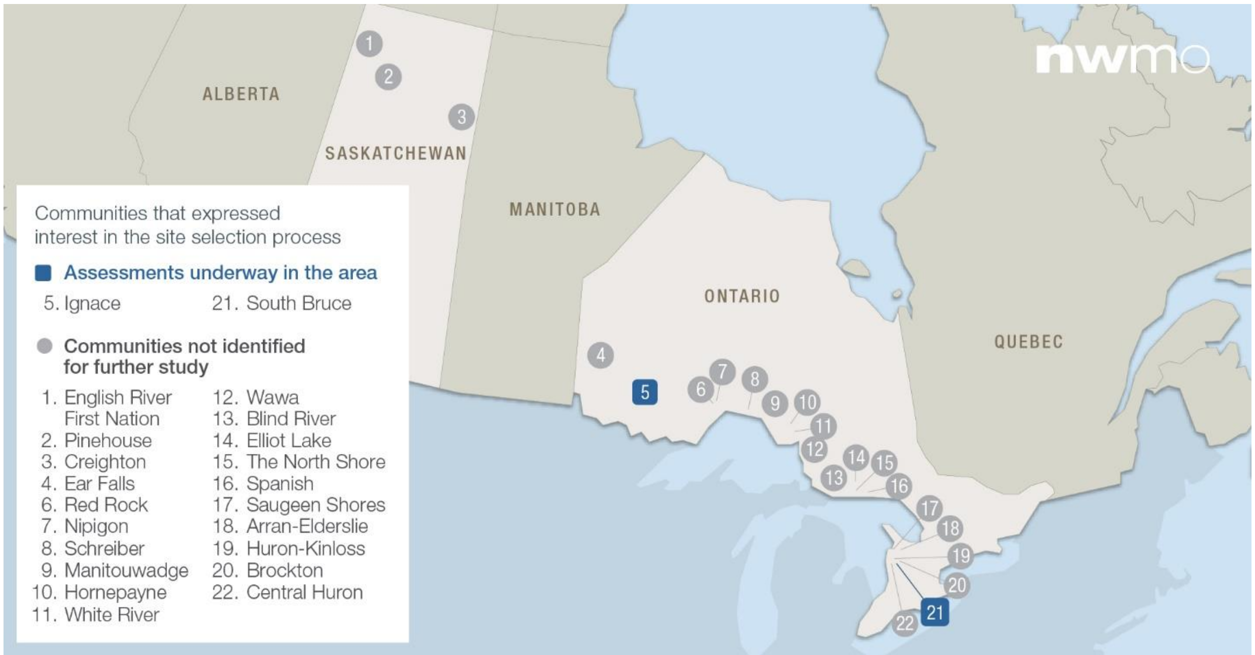


Figure 1-2: Interested Community Status as of 31 December 2021

2 OVERVIEW OF NWMO TECHNICAL PROGRAMS

The APM Technical Program includes site investigations, preliminary design and proof testing, and developing the safety case for a used fuel DGR. Work conducted during 2021 is summarized in this report. Prior years work is summarized in NWMO (2021b).

The work is summarized in the following sections divided into Engineering, Geoscience, Repository Safety, and Site Assessment.

This work involved 17 universities (including 15 Canadian universities), as well as a variety of industrial and governmental research partners. A list of the 2021 technical reports produced by NWMO is provided in Appendix A.1. Appendix A.2 provides a list of journal articles on work supported by NWMO.

An important aspect of the NWMO's technical program is collaboration with radioactive waste management organizations in other countries. In 2021, the NWMO had agreements with ANDRA (France), INER (Taiwan), KORAD (South Korea), Nagra (Switzerland), NDA (United Kingdom), NUMO (Japan), ONDRAF (Belgium) and SKB (Sweden) to exchange information arising from their respective national programs to develop a deep geologic repository for nuclear waste.

Some of this collaboration is work undertaken at underground research facilities. In 2021, NWMO supported projects at the Mont Terri Underground Rock Laboratory in Switzerland, the SKB Äspö Hard Rock Laboratory in Sweden, the ONKALO facility in Finland, and the Grimsel Test Site (GTS) in Switzerland. These provide information in both crystalline (Äspö, ONKALO, GTS) and sedimentary (Mont Terri) geological environments.

NWMO was involved with the following joint experimental projects in 2021:

- Full-scale In-Situ System Test (FISST/EBBO) demonstration project at ONKALO,
- The Mont Terri Project and Rock Laboratory including:
    - Diffusion across 10-year-old concrete/claystone interface (CI, CI-D),
    - Long-term Diffusion experiment (DR-B),
    - Analysis of Geochemical Data (GD)
    - Geomechanical in-situ Characterization of Opalinus Clay (GC-A)
    - Full Scale Emplacement Experiment (FE-G, FE-M),
    - Hydrogen Transfer (HT) test,
    - Iron Corrosion – Bentonite (IC-A) test,
    - Long-term Pressure Monitoring (LP-A),
    - Microbial Activity (MA),
    - Porewater Gas-characterisation Methods for Reactive and Noble Gases (PC-D),
    - Seismic imaging ahead of and around underground infrastructure (SI-A)
    - Permanent nanoseismic monitoring (SM-C), and
    - Large-scale Sandwich seal experiment (SW-A).
- POST Project (Fracture Parameterization for Repository Design & Post-closure Analysis),
- Materials Corrosion Test (MaCoTe) at GTS.
- Gas-Permeable Seal Test (GAST) at GTS.
- Enhanced Sealing Project (ESP) at Whiteshell Labs, Canada,
- MICA Michigan International Copper Analogue project, and

- International Bentonite Longevity project.

NWMO was involved with the following modelling or information exchange projects in 2021:
- DECOVALEX thermal-hydraulic-mechanical modelling,
- Aspo Groundwater Modelling Task Force,
- Post-closure criticality working group,
- CatchNET cold climate hydrology modelling,
- BIOPROTA biosphere models, and
- Joint projects with SKB on modelling fractured rock, including HM coupling, Skempton/Biot coefficient, fracture statistics.

The 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 the major nuclear energy countries, including waste owners and regulators. NWMO is involved with the following NEA activities:

- Radioactive Waste Management Committee (RWMC),
- Integration Group for the Safety Case (IGSC),
- Working Group on the Characterization, the Understanding and the Performance of Argillaceous Rocks as Repository Host Formations (i.e., Clay Club),
- Expert Group on Geological Repositories in Crystalline Rock Formations (i.e., Crystalline Club),
- Expert Group on Operational Safety (EGOS),
- Thermodynamic/Sorption Database Development (TDB) Project, and
- Working Party on Information, Data and Knowledge Management (WP-IDKM).

This report aligns with the RD2019 - NWMO's Program for Research and Development for Long Term Management of Used Nuclear Fuel (NWMO 2019). The RD2019 report describes the major technical research and development directions of the NWMO. It is complementary to NWMO activities in site selection, site characterization, design and engineering proof testing, and considers the full lifecycle of the repository. A key point is that underlying science studies will continue throughout the repository phases in order to support future licence decisions. The current annual technical report includes an update on work that supports this science basis.

3 REPOSITORY ENGINEERING AND DESIGN

During 2021, research and development progressed in the Engineering Program according to Plan. Work continued in the primary areas of the program and new work was initiated on the development of Design Requirements (DR) for the DGR, Used Fuel Packaging Plant (UFPP) and the Used Fuel Transportation System (UFTS). Major activities in the overall work program cover: transportation of fuel and logistics, used fuel container (UFC) design, manufacturing, and commencement of the fabrication of 15 UFCs; manufacturing of equipment for the demonstration of the engineering barrier systems, buffer and sealing systems for the mock-up emplacement of bentonite buffer and sealing systems at the NWMO Oakville facility; support work for the development of two conceptual design DGRs at two sites; and the detailing and optimization of the UFPP. Summaries of these activities in 2021 are provided in the following sections.

3.1 DESIGN REQUIREMENTS

In 2021, three high-level design requirements (DR) documents were developed. They provide the basis for the development of more detailed sub-tier design requirements and program requirements, and will be used to inform safety assessment, site evaluation, and project cost estimate updates.

1. <u>APM DGR Project Level DR</u>

The APM DGR Project DR document identifies the design basis of the APM DGR and the overarching project-level requirements for on-site surface and underground facilities (i.e., within the peripheral fence), the supporting off-site facilities (e.g., the excavated rock management area and the Center of Expertise), and the transportation program. The document also provides an overview on the APM project stages, major activities, and key functional systems.

2. <u>Used Fuel Packaging Plant (UFPP) DR</u>

The UFPP DR document identifies the design basis and requirements of the UFPP. This encompasses the structures, systems, components, materials, processes, procedures, and other aspects necessary to achieve the safe receipt and repackaging of used fuel for placement in the DGR. The primary UFPP functions include receipt and processing of transportation packages, handling of the used fuel bundles, repackaging of the used fuel into the UFC, assembly of the completed UFC into the bentonite Buffer Box (BB), and dispatch of the UFC and BB assembly for placement into the repository.

3. <u>Used Fuel Transportation System (UFTS) DR</u>

The UFTS DR document identifies the design basis of the UFTS which encompasses the structures, systems, components, materials, processes, procedures, and other aspects that constitute the means by which the safe movement of used fuel between the APM DGR and interim storage facilities is achieved, where those facilities may include the nuclear power stations and the radioactive waste-storage facilities.

3.2 USED FUEL TRANSPORTATION

3.2.1 Used Fuel Transportation Systems

Canada’s used nuclear fuel is currently safely managed in facilities licensed for interim storage. These facilities are located at nuclear reactor sites in Ontario, Québec, and New Brunswick, as well as Atomic Energy of Canada Limited’s nuclear sites at Whiteshell Laboratories in Manitoba, and Chalk River Laboratories in Ontario. The long-term management of Canada’s used nuclear fuel will require transport of the used nuclear fuel from these interim storage facilities to the DGR.

NWMO is currently in a site selection process for the repository and has narrowed its focus to two potential siting areas: the WLON-Ignace area in northwestern Ontario; and the SON-South Bruce area in southern Ontario. The locations of the interim storage facilities and the potential siting areas are illustrated in Figure 3-1.

Figure 3-1: Interim Storage Facilities and Potential Siting Areas

NWMO’s current reference Used Fuel Transportation System (UFTS) is an all-road system which uses two types of transportation packages: Used Fuel Transportation Packages (UFTPs) for OPG owned fuel; and a conceptual Basket Transportation Packages (BTPs) for all other fuel. Both UFTPs and BTPs are to be transported using conventional tractor-trailers.

An alternative UFTS is being considered by the NWMO which uses Dry Storage Container Transportation Package (DSC-TP) for the transport of OPG owned fuel currently stored in Dry Storage Containers (DSCs). Superload or heavy-load trucks and railcars are being considered for these DSC-TP shipments. As in the reference UFTS, conceptual BTPs are to be used to transport non-OPG owned fuel, on conventional tractor-trailers.

NWMO's responsibility includes the development of a robust UFTS to ensure the safe and secure transport of Canada's used fuel. Projects in the areas of transportation routing, estimating transportation environmental releases; transportation security as well as supporting the Whiteshell Fuel Transfer Project were all areas of work in 2021.

3.2.2 Used Fuel Transportation System – Routing Assessment

NWMO initiated an assessment aimed at scoping representative primary and alternative routes from each interim storage facility to both potential repository site locations, for the two UFTS concepts being considered, as described above.

The assessment uses diverse routing considerations and factors identified through a literature review, including safety criteria, benchmarking against established industry programs, criteria identified through public engagement, technical factors and regulatory guidance, before applying them via a robust methodology. Following application of the methodology, recommended options for preferred and alternative routes are identified. This project is ongoing and anticipated to be completed in 2022.

3.2.3 Used Fuel Transportation System – Estimates of Environmental Releases

Concurrent to the routing assessment, a preliminary analysis of environmental releases was initiated based on established representative routes and proposed activities in order to quantify estimates of conventional (non-radiological) environmental releases resulting from the construction, operation, maintenance, and decommissioning of the UFTS concepts.

In addition, other transportation technologies (such as use of hydrogen or electric powered conveyances) and related implementation challenges were assessed. This project is ongoing and anticipated to be completed in 2022.

3.2.4 Used Fuel Transportation Security Framework

The Used Fuel Transportation Security Framework project was initiated to provide a foundation of knowledge upon which a security framework for the transport of Canada's used nuclear fuel can be developed. The intent of this work is to define the transportation security requirements, provisions, and components of a robust transportation program.

Using the existing transportation security regulations, industry best practices and operational experiences as a basis, a conceptual transportation security framework is being developed based on the UFTS designs being considered. Road and rail modes of transport, intermodal (road/rail) transfers, and return shipments are considered. Initiated late in 2021, this project is ongoing and is anticipated to be completed in 2022.

3.2.5 Whiteshell Fuel Transfer Project

NWMO is currently collaborating with Canadian Nuclear Laboratories (CNL) to support the Whiteshell Fuel Transfer Project aimed to consolidate used fuel storage. Used fuel currently stored at Whiteshell Laboratories in Pinawa, Manitoba will be transported to the interim waste management facility in Chalk River, Ontario. To accomplish this, CNL has leased NWMO's Used Fuel Transportation Package (UFTP-1). The first phase of the project involves the transport of used natural uranium CANDU fuel originally from the Douglas Point reactor.

Preparation of the UFTP for transport operations has included commissioning of UFTP-1 for first use. These commissioning activities have provided NWMO with valuable experience which have led to updates of the UFTP's design basis documentation. An amended Type B(U) certificate which includes the Phase 1 fuel was obtained for the UFTP from the Canadian Nuclear Safety Commission (CNSC).

3.3 USED FUEL PACKAGING PLANT

The Used Fuel Packaging Plant (UFPP) is a key facility at the DGR site for the long-term storage of used fuel. The UFPP will have all the provisions required for receiving the transportation casks known as Used Fuel Transportation Packages (UFTP) for fuel being transported in storage modules or Basket Transportation Packages (BTP) for fuel in sealed baskets, equipment for fuel handling, designated facilities for the encapsulation of the fuel in Used Fuel Containers (UFCs) and their dispatching for emplacement in the DGR.

The NWMO completed its first iteration of the conceptual design for the UFPP in early 2021. The overall conceptual layout of the UFPP is shown in Figure 3-2. The process operations for handling the used fuel and its encapsulation in the UFCs are described in the Annual Technical Report for 2020 (NWMO, 2021b).

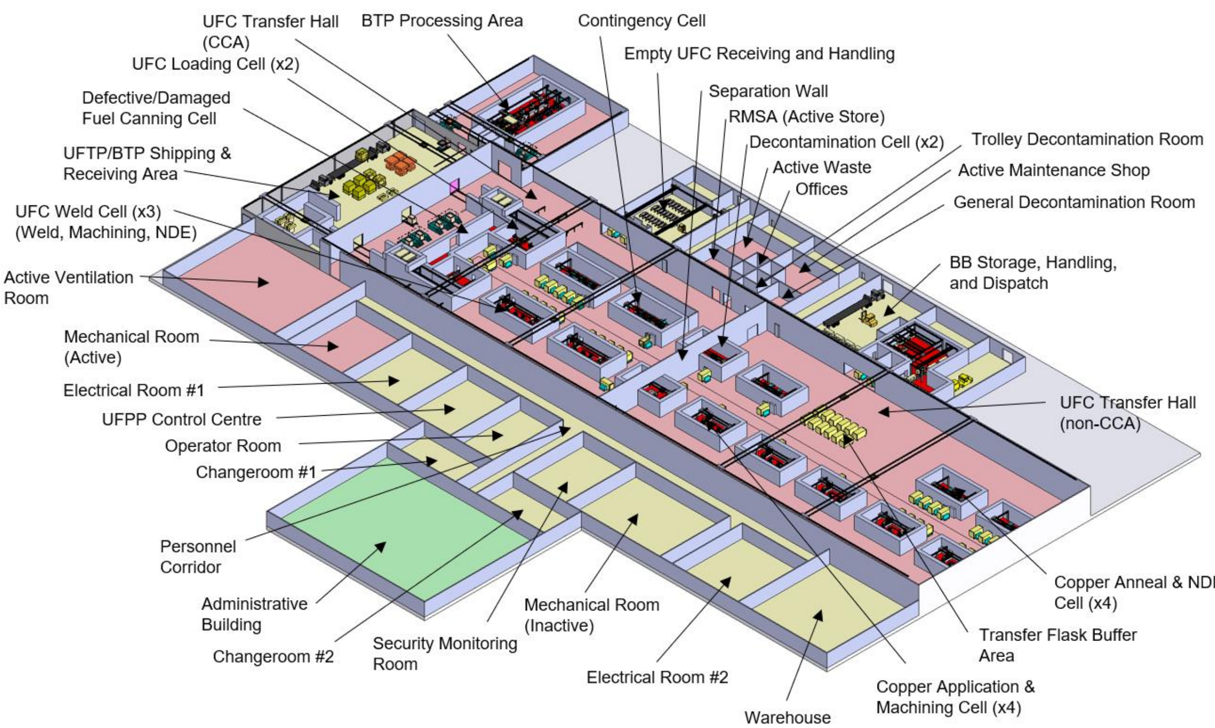


Figure 3-2: Concept Layout of the Used Fuel Packaging Plant (UFPP)*

*The key acronyms denoting processing areas and components are: CCA (Contamination-controlled Area), Non-CCA (non-contaminated control area), BB (Buffer Box), BTP (Basket Transportation Package), UFTP (Used Fuel Transportation Package), UFC (Used Fuel Container), NDE (Non-destructive Examination), and RMSA (Radioactive Material Storage Area).

The UFPP reference concept design, the first iteration of the UFPP, was developed to satisfy specific design restrictions and requirements. Evaluations to assess the viability of alternative plant layouts and Used Fuel Container (UFC) handling processes have not been completed to date. During the review process for the concept design, several areas for improvements were identified, which led to an optioneering study to examine alternative methods of UFC handling, transfers and logistics. The main purpose of the transfer hall is to facilitates the movement of UFCs loaded with used fuel between the packaging processes within the UFPP. These transfers occur using a combination of shielded transfer casks and in-cell transfer equipment in the shielded process rooms.

3.3.1 Options Evaluation

The 2021 conceptual design of the UFPP represents the NWMO's first iteration of the UFPP primary process flow and therefore it was necessary to explore opportunities for optimization. The two key factors investigated were the number of transfers between shielded process rooms and transfer casks and the usage of in-cell handling tools.

The work includes the following steps:

1. OPEX consolidation
2. Options study
3. Options evaluation and analysis

3.3.1.1 OPEX Consolidation

Operating methodologies from several domestic and international facilities that handle large radioactive packages for the purpose of processing were assessed and consolidated into an OPEX report. The emphasis was on understanding several principles incorporated in these other facility designs:

1. What was the method employed to transfer the radiological packages?

   Other facilities employed a number of different methods including using rail and trolley systems, shielded cask on automated guided vehicles and cranes with specialized grappling devices.

2. What type of facility layout or process flow were utilized?

   There are a number of different types of facility layouts used to advance radioactive packages through their respective processes. Some approached it with a modular layout, others had dedicated line(s).

   A number of nuclear facilities made use of multiple levels, included dedicated operations or maintenance floors to handle the nuclear materials and/or equipment. This would be considered when optimizing the UFPP layout.

3. What was the primary contamination control strategy used?

   Contamination control methods used at other facilities were reviewed for applicability to the UFPP. Contamination control systems maintain the boundary between clean areas and areas which would have contamination.

Different facilities also employed decontamination at various points of their process.

4. What was the primary means which maintenance would be performed?

   Some facilities operated with remote maintenance for their equipment. Others maintained their equipment with generally manual methods where they would bring the equipment out of the shielded area or enter the shielded areas when it was safe to do so.

5. What was the philosophy for recovering from abnormal operating conditions?

   The equipment in the facility may fail between maintenance cycles and recovery from these abnormal events must be rectified. Similar to maintenance, recovery from abnormal operating conditions must recover and remove the equipment from the shielded area for repair or enter the shielded area when it is safe to do so.

3.3.1.2 Options Study

The additional knowledge gained from investigating the other nuclear facilities helped develop alternative options for the transfer hall. A preliminary evaluation was conducted to determine which options would be further developed. Three layouts were chosen to be further developed and evaluated against the current reference design: a single assembly line (see Figure 3-3); parallel lines (see Figure 3-4; and a modular configuration (see Figure 3-5). These layouts were designed to provide details for the option evaluation. The analysis conducted include determining the major systems required to meet the throughput and the space necessary to house the equipment. Calculations were done to help support the qualitative analysis of each layout.

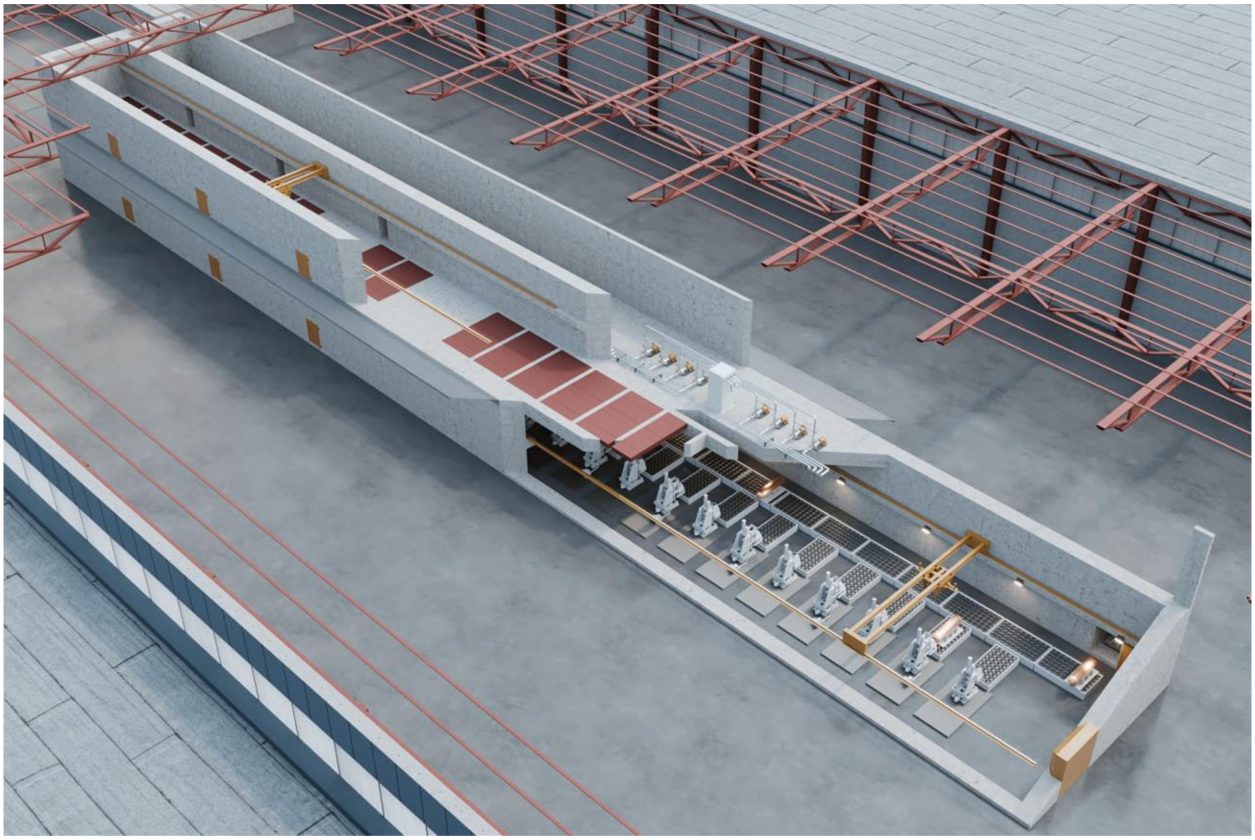


Figure 3-3: Illustration of Potential Used Fuel Packaging Process in an Assembly Line Layout. Final Design May Not be Exactly as Shown

Figure 3-4: Illustration of Potential Used Fuel Packaging Process in a Parallel Line Layout. Final Design May Not be Exactly as Shown

Figure 3-5: Illustration of Potential Used Fuel Packaging Process in a Modular Layout. Final Design May Not be Exactly as Shown

3.3.1.3 Option Evaluation

A systematic approach was taken to determine the suitability of each option to meet the UFPP design requirement. The risks and trade-offs of each option were individually compared and scored. Optimization of each option were not completed. The parameters compared were:

Radiological safety – where would operational staff most likely to receive a dose uptake or contamination exposure?

Conventional safety – what and where are operational staff most likely to be subjected to industrial hazards?

Operational reliability – what aspects of the layout would contribute to the reliability of the facility during the operational period and what would their impacts be?

Maintainability – how must operational staff maintain the facility and what is the impact on operations?

Cost – what is the expected impact on overall cost and what are the driving factors?

Flexibility and novelty – how would each layout impact the UFPP's ability to adapt to new processes as we pursue advancement in technology and how does each layout compare to other facilities in industry?

The environmental impact of each layout was also assessed, but all options were relatively equal – there were not distinguishing features between the layouts for comparison.

3.4 BUFFER AND SEALING SYSTEMS

The NWMO continues to support the development of the buffer and sealing systems including optimized manufacturing, storage, and emplacement technology for the Highly Compacted Bentonite (HCB) blocks that are placed directly around the UFCs.

The gapfill material delivery equipment was designed, and fabrication initiated. An emplacement plan for a large-scale demonstration trial was produced, defining the scope of the emplacement plan as well as schedule and expected costs. A delivery system for smaller HCB bricks was designed and built.

3.4.1 Emplacement Equipment

The prototype emplacement equipment was designed and built by Medatech Engineering Services (Collingwood, Ontario, Canada) to NWMO requirements, and tested at the NWMO Oakville Facility. Further enhancements will be implemented for the emplacement equipment to increase forward visibility and provide enhancements to the steering system for fine control.

3.4.2 Emplacement Plan

The purpose of this work was to define the scope of the emplacement demonstration. The plan was reviewed internally and by a third party for a comprehensive benchmarking review against their own experience in demonstration programs. The review identified some opportunities to obtain more quantitative data with enhancements to equipment. The opportunities were adopted in the test plan and are being reflected in updates to the equipment.

3.4.2.1 Background

3.4.2.1.1 Bentonite

The NWMO has continued to accept large volumes of unprocessed and fabricated bentonite materials into the NWMO research and development facility in Oakville, as a component of the Proof Test Plan. These materials consist of:

(i) Granular MX-80 bentonite;
(ii) HCB Blocks delivered from the Penn State compression facility for shaping; and
(iii) Crushed granular MX-80 based Gap Fill Material (GFM).

Given the volume of material, there is a need to conduct a testing program in order to identify sub-standard material, and further refine the frequency of testing as well as material specifications for future Quality Control programs. In 2020, the NWMO initiated a testing program based on ASTM methods on delivered bentonite materials as follows: (i) moisture content, (ii) grain size analysis, (iii) consistency limits, (iv) methylene blue tests, (v) free swell, (vi) mineralogical and chemical composition, and (vii) dry density.

3.4.2.1.2 HCB Blocks

HCB blocks are pressed from raw MX-80 sodium bentonite. The raw bentonite is sourced from the United States at a moisture content of 10-12% ($m_{water}/m_{dry\ solid}$). It is then up-blended with water to bring the moisture content up to 20%. This blending work is performed by a local food blending company in a large industrial blender. The blended bentonite returns to the NWMO proof test facility in tote bags where it is loaded into an isostatic pressing bag and form assembly. Once the bag is filled, air is withdrawn and the bag sealed, it is sent to Pennsylvania State University to be cold isostatically pressed at their High Pressure Test Facility. The bentonite is pressed at 100 MPa in their 60 inch diameter pressure vessel which results in an HCB block with a dry density ≥1.74 g/cm^3 (Figure 3-6). To date, over twenty full size blocks have been pressed using cold isostatic hydraulic press technology. Block yield has been approximately 90%.

The isostatic pressing produces a block that is "near net shaped," meaning it is close to the final desired shape. The blocks are machined to final dimensions for the Buffer Box assembly in the robotic milling cell at the NWMO Oakville test facility (Figure 3-7).

Figure 3-6: Highly Compacted Bentonite (HCB) Block

Figure 3-7: Shaped Highly Compacted Bentonite (HCB) Block

The shaping productivity is improved, and the shaping process has become more reliable in 2021, benefitting from continued troubleshooting. Seventeen blocks have been shaped by the end of November 2021, which exceeds this year's objective of sixteen shaped blocks (Figure 3-8). The shaping cell software modification made in 2020 has solved the issues identified in the previous years. The troubleshooting cases number reduced to eight in 2020 and further reduced to three this year. Minor troubleshooting cases have minimized downtime, which benefits the average shaping time, reducing it to thirty hours in 2021 from fifty hours in 2019.

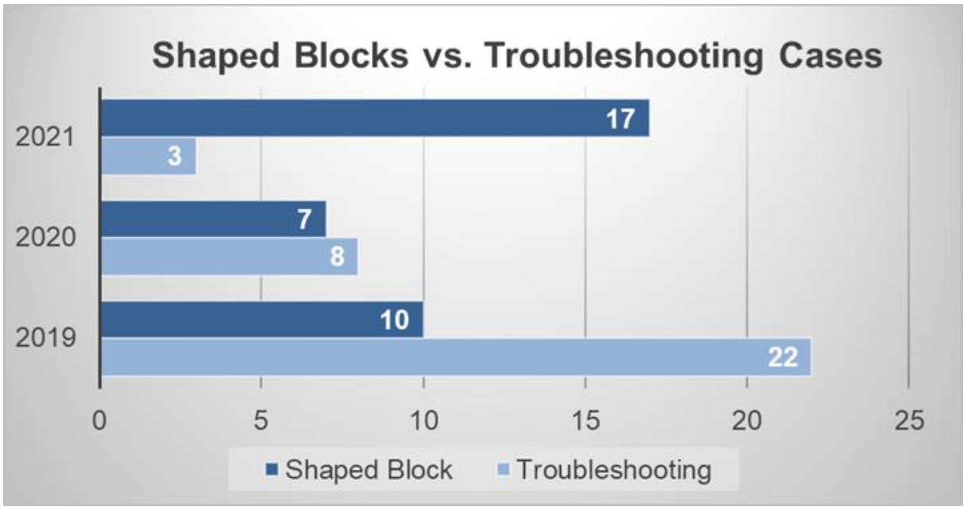


Figure 3-8: Shaped Block vs. Troubleshooting Cases

3.4.2.1.3 Used Fuel Container

The engineered barrier closest to the fuel is the used fuel container (Figure 4-1 and Figure 4-2). Its safety function is containment and isolation. It fulfills the safety function by incorporating the corrosion barrier and the structural vessel to meet performance requirements. The used fuel container is a mid-sized capacity (12 bundle/layer x 4 layers = 48 bundle) vessel which incorporates a steel core for structural strength and a 3 mm exterior copper coating for corrosion resistance. The weight of the container loaded with fuel is approximately 2,800 kg.

3.4.2.1.4 Buffer Block Assembly

The buffer box assembly (Figure 3-9) is two highly compacted bentonite blocks containing a used fuel container.

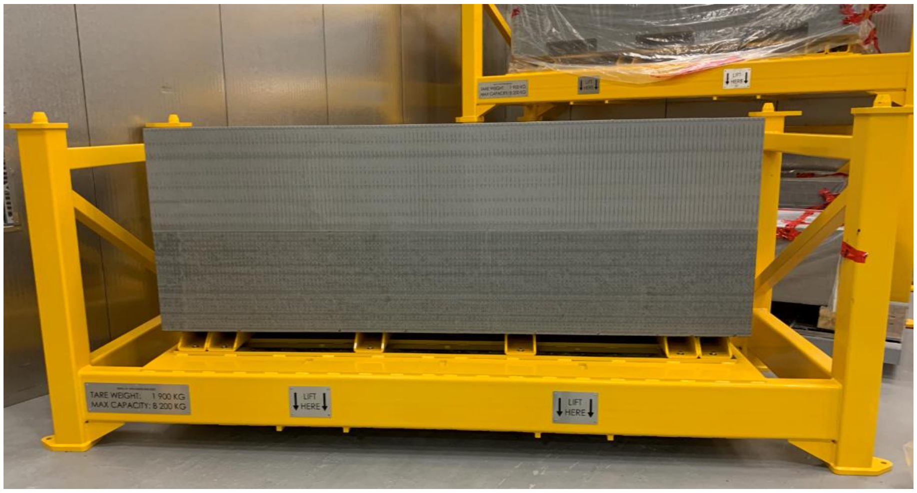


Figure 3-9: Buffer Box Assembly

The HCB blocks and Used Fuel Containers have no lifting features and generally cannot be handled with conventional equipment without damage. The Buffer Box is therefore assembled with vacuum lifting equipment. The vacuum lift is capable of lifting the HCB (Figure 3-10 on either the bottom flat surface or on the top cavity surface, and with a vacuum pad change, it can pick up the UFC (Figure 3-11). The unit is purpose built and battery powered. The vacuum lift is fabricated by the Vacuum Lifting Company SF4KB unit with a safe working load rating of 4200 kg with the HCB vacuum pad.

Figure 3-10: Vacuum Lift Highly Compacted Bentonite (HCB)

Figure 3-11: Vacuum Lift Used Fuel Container (UFC)

To lift the HCB block with step features, a new custom attachment was fabricated in 2021 (see Figure 3-12). The attachment uses several smaller pads to attach for lifting the HCB blocks with the machined forklift pockets. This allows lifting the shaped block in two configurations: The larger vacuum pads are used to lift the block from forklift pockets, and the narrow vacuum pads are used to lift the block from the block bottom surface.

Figure 3-12: Vacuum Lift HCB Block with Pockets

3.4.2.1.5 HCB Block Storage

HCB blocks are sensitive to humidity**.** Once the HCB blocks are removed from the pressing bag, they need to be stored in a location where the vapour pressure of water in air is in equilibrium with the vapour pressure of the water in the block. This is accomplished by storing the HCB blocks in a humidity-controlled room and maintaining the relative humidity above 70% at 20°C.

3.4.2.1.6 Mock Emplacement Room

The NMWO has fabricated a mock emplacement room in Oakville for testing (Figure 3-13). The mock emplacement room simulates the anticipated dimensions, as well as the drill and blast profile of underground excavation. The resulting rock surface is rough with near 90 degree angles at the "lookouts" (i.e., sharp profile changes due to the drill and blast process).

Figure 3-13: Simulated emplacement room with faux rock walls simulated drill and blast profile. (a) Exterior steel frame approximately 3m x 3m x 15m in size; (b) Interior with faux rock walls and (c) Actual rock wall profile from underground research laboratory

3.4.2.1.7 Buffer Box Delivery Tooling

The buffer box delivery tooling, or buffer box attachment, is a custom engineered forklift attachment that is used with the electric Versa Lift 25/35 lift truck at the NWMO Oakville test facility (Figure 3-14). It was designed specifically to lift and place Buffer Box assemblies. It features:

1. Three 16 inch wide, adjustable/removable tines with independent hydraulic load levelling.
2. Inflatable air bags to apply a compressive load to the ends of the buffer box assembly
3. Five cameras and three alignment lasers to allow remote placement of the buffer box assembly using the Versa Lift's remote control pendant.

The attachment was designed and built as a research tool, as such, it has many features that can be changed including, adjustable/removal of tines to allow test flexibility, adjustable bag pressure, different tine configurations, etc. Buffer boxes with 2 or 3 pockets can be used and the tines can be repositioned along the width of the buffer box. This feature allows testing of several different configurations before settling on a 'reference' design.

The inflatable airbags apply a compressive load of up to 1000 kg to the ends of the buffer box assembly. This load helps with sagging of the buffer box, depending on the position of the tines, but more importantly, prevents the HCB from separating should there be a crack or a break.

Since in the future this equipment will have to be remotely operated due to the high radiation fields, it is important to demonstrate that the buffer boxes can be placed remotely. The cameras and lasers help the operator drive the vehicle and correctly position it to place the buffer box.

Figure 3-14: Buffer Box Attachment installed on Versa Lift 25/35

In 2021, the buffer box delivery tooling was modified in two ways. First, the equipment was modified to self-steer down the length of the emplacement room, and secondly, the equipment was modified to sense the floor tablets, or previously placed buffer box, to help with forward placement of the next buffer box assembly.

These changes were accomplished controlling the steering, mast tilt, mast lift and mast side shift with a new CAN directional valve and a new purpose designed radio to control them. Sensors were incorporated into the front of the forklift enabling it to determine its position from an object, providing the operator with a digital readout. When positioning a buffer box on top of another, the operator is provided with a readout of the load height and indicator of when the load is within a safe height to be placed.

These changes were tested, and the equipment commissioned in September 2021. As part of these tests, an in-room stacking trial was performed, which was the first time buffer boxes were stacked by equipment inside the emplacement room (Figure 3-15).

Figure 3-15: Completed Stacking Trial, 2 Buffer Boxes Stacked in the Emplacement Room

3.4.2.2 Fork Pocket Brick Delivery Equipment

To fill the voids left to accommodate the buffer box delivery equipment, HCB bricks must be inserted into the fork pocket void. This will be performed by a custom-built cart capable of lifting the bricks and pushing them into the space with an electric screw (see Figure 3-16). The equipment has been designed, built and placed in service.

Figure 3-16: Fork Pocket Brick Delivery Equipment

3.4.2.3 Gapfill Delivery Equipment (Auger System)

The final major component necessary for the full scale emplacement demonstration is an auger system to deliver the gapfill to the residual space between the rock face and the emplaced buffer boxes. The system was designed in 2020 and was fabricated and initial testing performed in October 2021. The equipment travels on rails into the emplacement room and places gap fill material in the space between the buffer boxes and the interior walls and ceiling of the mock emplacement room. The gap fill delivery equipment is a complex piece of equipment with many systems.

For the precision required to fit between the buffer boxes and the interior walls and ceiling of the emplacement room, the equipment travels on rails. The gap fill material is stored in hoppers, which is then delivered by feeding screws. The feeding screws are primarily to get the material into the room where the vibrating rods densify the material in place. The vibrating rods are pneumatically powered by a self-contained air compressor. To minimize dust, the equipment has a dust collection system. The equipment is also equipped with lights, cameras, and sensors to give the operator a complete picture of what is occurring at the front of the machine. The feedback of the sensors and feeding screw loads help determine the rate at which to retract the machine. The machine fills approximately one meter of room before it has to be removed to place a row of buffer boxes. A scale is used to measure the amount of material loaded and delivered by the equipment. See Figure 3-17 for an image of the auger system and Figure 3-18 of the equipment installed in the NMWO Oakville test facility.

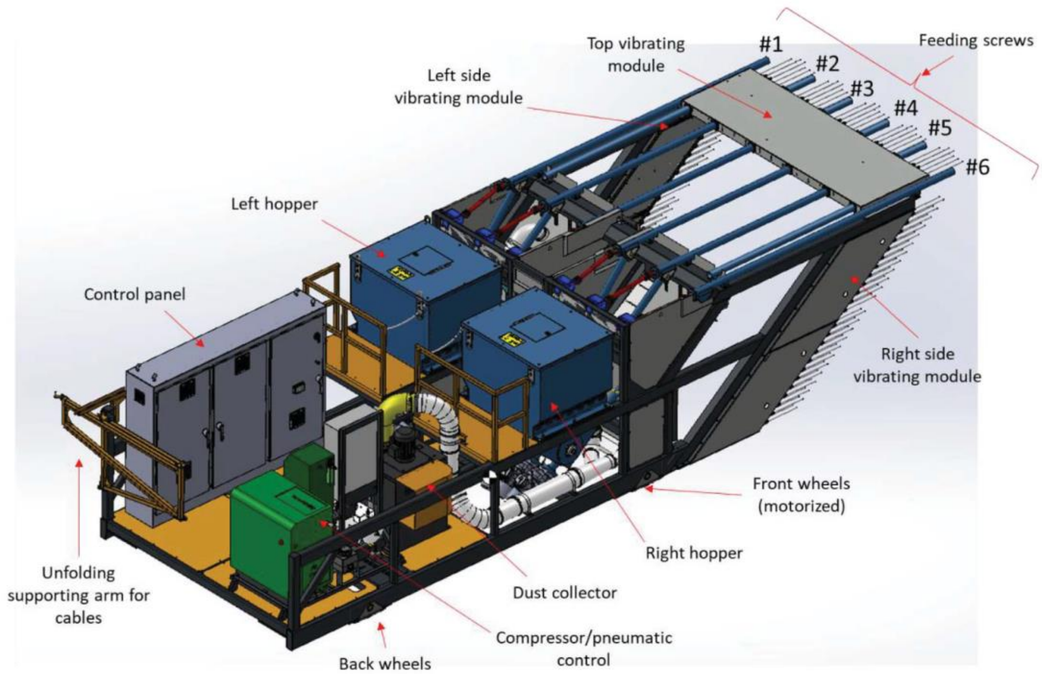


Figure 3-17: Gapfill Delivery Equipment (Auger System)

Figure 3-18: Gap Fill Delivery Equipment in Oakville Test Facility

3.5 SITE AND REPOSITORY

3.5.1 Deep Geological Repository Conceptual Design Report Crystalline/Sedimentary Rock

NWMO has prepared a conceptual report that describes designs for a DGR facility in either crystalline or sedimentary rock (NWMO, 2021c). For costing purposes, it is assumed that the facility will receive 5.5 million used CANDU fuel bundles over a 46-year period. The report describes the required surface facilities and infrastructure shown in Figure 3-19 needed to safely receive and, package, the used nuclear fuel in the Buffer Box concept (Figure 3-20). Details of the underground placement concept have also been presented including the conceptual underground emplacement layout shown Figure 3-21. At the end of emplacement activities and following a period of extended monitoring the DGR facility will be decommissioned and closed. All underground space, including the rooms, tunnels and the three shafts will be permanently sealed.

Figure 3-19: Deep Geological Repository (DGR) Main Surface Facilities

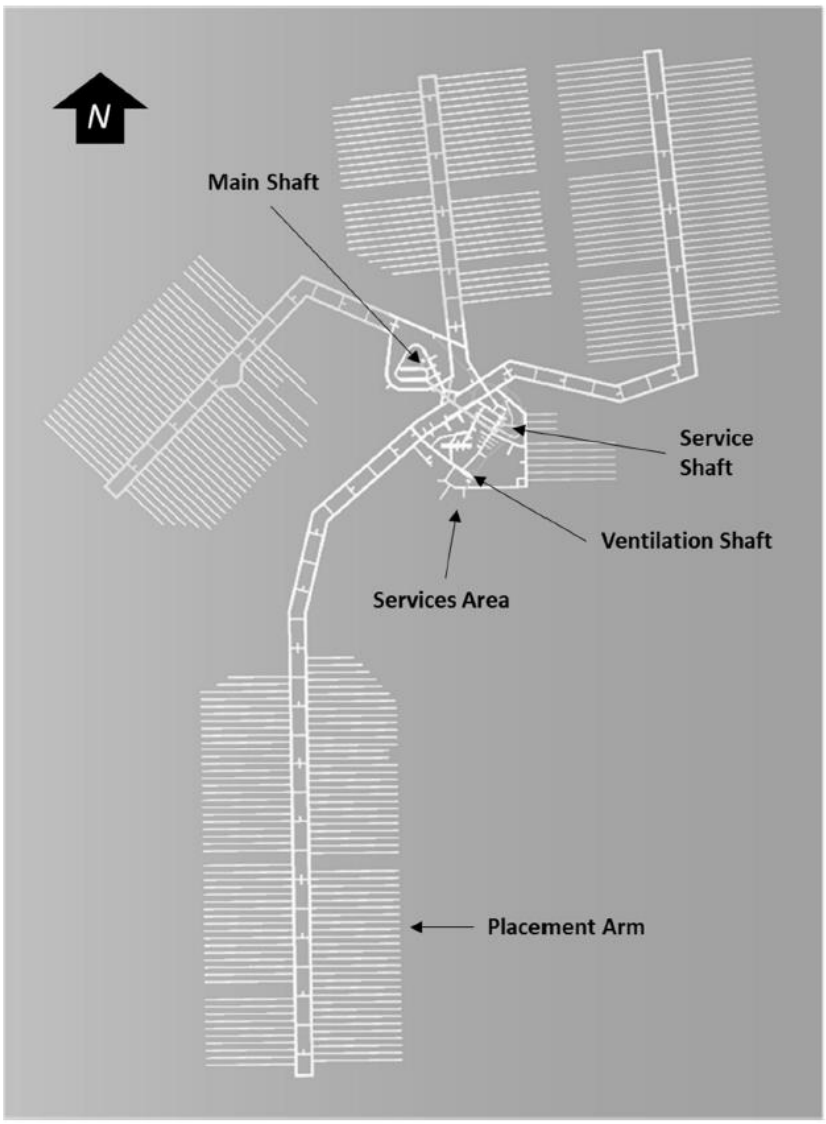


Figure 3-20: Underground Repository Layout Concept (Crystalline Rock Geosphere)

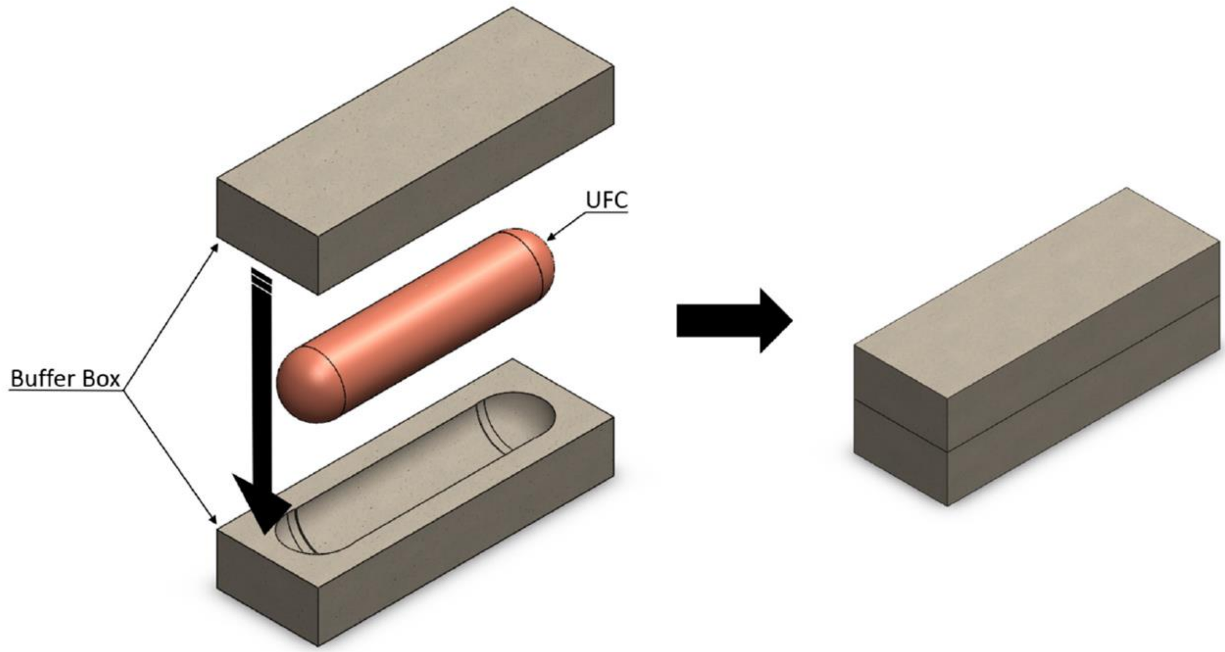


Figure 3-21: Used Fuel Container within Bentonite Buffer Box

3.5.2 Sealing Materials Receipt, Storage and Preparation Systems

An update to the APM DGR, Conceptual Design for the Sealing Materials Receipt, Storage and Preparation was carried out. The updates reflect the recent developments used in the production of the buffer boxes under pilot trial conditions developed by the NWMO. The work reflects the DGR layouts for the two proposed sites and the updated concepts for engineered barrier sealing systems.

3.5.3 Electrical Load Demand Estimates

The purpose of this work was to estimate the Electrical Power Demand for the APM project. This considered electrical demand from various surface and underground facilities and operations.

The peak power demand was estimated to be 28,700 kW including contingency and allowance factors.

3.5.4 Multiple Design Requirement Documents

In 2021, the NWMO continued to develop the repository designs for the two specific sites. As a component of this multi-year work program design requirements and criteria for various engineering scopes of work were established as follows:

1. Underground Services Area and Amenities Design Requirements – Crystalline
2. Service Shaft Hoisting and Loading Pocket System Design Requirements – Crystalline
3. Main Shaft Hoisting System Design Requirements – Crystalline
4. Exhaust Ventilation Shaft Hoisting System Design Requirements – Crystalline

5. Service Shaft Headframe Design Requirements – Crystalline
6. Main Shaft Headframe Design Requirements – Crystalline
7. Exhaust Ventilation Shaft Headframe Design Requirements – Crystalline
8. Water Treatment, Storage, and Distribution Design Requirements
9. Process and Stormwater Management Design Requirements

The intent of these documents is to present the requirements for the various components in order to develop a more detailed repository design.

3.5.5 Placement Room Concepts and Placement Techniques – Development to Final Sealing

This work focuses on the plan for developing the placement rooms, emplacing the used fuel, backfill, and seal, and most importantly identifying issues that may arise and how to deal with them. After completing a preliminary review of floor smoothing options, four methods identified by NWMO for placement room development and construction were studied and evaluated.

The four options were ranked using a Pugh Matrix and based on the following categories:

1. Constructability
2. Ability to meet bentonite dry density specification of 1.6 t/m3
3. Robustness during operations
4. Productivity – relative time to excavate and construct
5. Technology readiness

We are currently considering these options and will refine as our design advances.

3.5.6 Conceptual Design for Underground Repository in Crystalline Rock and Sedimentary Rock

A conceptual layout within a crystalline rock geosphere has been prepared. It advances the depth of study details where appropriate for this stage in the design process. In this update, the description of the DGR has been updated to reflect:

- The Services Area with the current versions of the Underground Demonstration Facilities (UDF), mobile and fixed equipment shops, and Used Fuel Container/Buffer Box (UFC/BB) transfer cask / trolley storage at the Main Shaft and Main Shaft Area access.

During the progression of this study, several design assumptions have been modified as the study progressed, for example:

- The assumption of diesel equipment for underground was used initially, and revised to assume all mobile equipment for development, construction and placement activities underground would be battery powered.

3.5.7 Traffic Study Inputs

This work provides the methodology and assumptions used to determine the inputs required to support a traffic study and community impact assessment for both the WLON-Ignace area and the SON-South Bruce area.

4 ENGINEERED BARRIER SYSTEM

The engineered barrier system (EBS) is a major component of the underground design. It includes the wasteform, container, buffer and sealing systems. Summaries of these activities are provided in the following sections. Wasteform durability is discussed in Section 6.2.

4.1 USED FUEL CONTAINER DURABILITY

In 2021, the NWMO continued the execution of the Proof Test Program to validate the reference design of the Used Fuel Container (shown in Figure 4-1). The demonstration of UFC manufacturing/inspection/testing via a Serial Production Campaign is ongoing. Progress in UFC Proof Testing, R&D and design analysis activities are summarized in the subsections below.

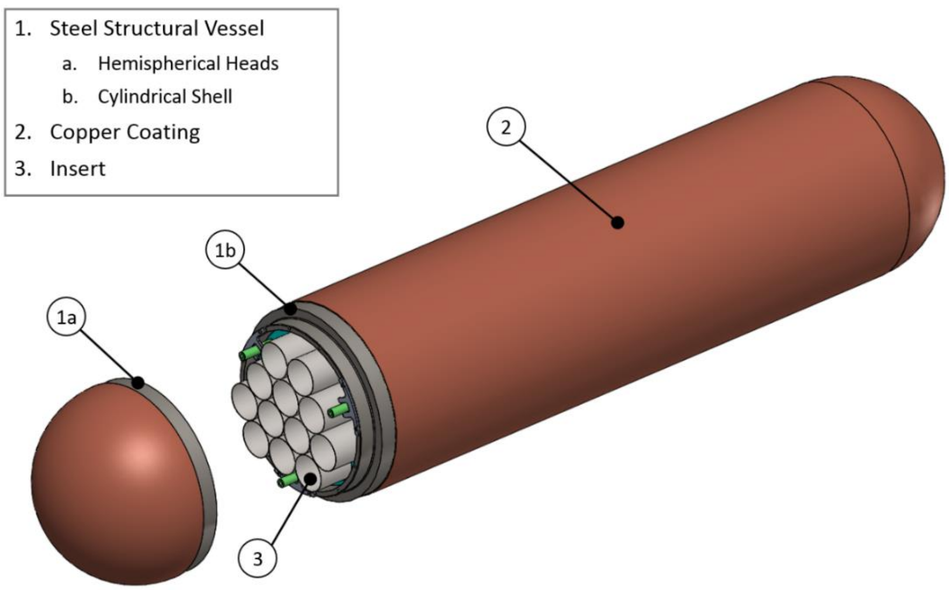


Figure 4-1: Illustration of Used Fuel Container Reference Design

4.1.1 UFC Design

In 2021, the NWMO UFC design team met with the CNSC to continue with the conversation on the regulator's technical review of the UFC design. The regulator provided further clarifications on their comments provided in 2019. The applicability of existing technical codes and standards, such as the ASME Boiler and Pressure Vessel Code (BPVC), to the design of the UFC was discussed. It was proposed that the NWMO prepares documentation, e.g., white paper to: *i)* describe the design philosophy of the UFC; *ii)* provide explanations on how NWMO's UFC design criteria were established; and *iii)* identify the contents of the existing standards that can be applied to the UFC construction.

Design analysis on the UFC continued progressing in 2021, which included the uneven buffer swelling analysis, a more refined stress analysis for the glacial loading, and a preliminary sensitivity study on non-uniform external pressure on the UFC. A simulation of the closure welding process and the subsequent pressurization of the internal air in the UFC was also conducted to determine whether a temporary venting port needs to be considered in the fabrication process.

4.1.2 UFC Serial Production Campaign

4.1.2.1 Fabrication of UFC Prototypes

In 2021, the NWMO continued the execution of its UFC Serial Production campaign. In this past year, one UFC was completed (Figure 4-2) and the balance of fifteen UFC's are in various stages of assembly. Ongoing feedback from serial production and parallel R&D programs is allowing further optimization of select manufacturing processes which are being implemented in subsequent UFC units.

Figure 4-2: Used Fuel Container Reference Design – Serial Production Unit #1

Throughout the Serial Production campaign in 2021, drawings, manufacturing, inspection & test plans, and related documentation such as procedures and inspection report templates were created and revised to support machining, welding, copper coating, and non-destructive examination (NDE) work on UFC components.

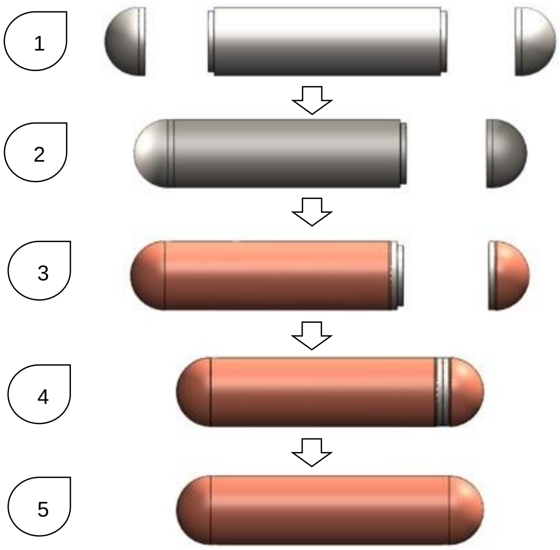
In 2021, an alteration was made to the plan for fabrication of 5 of the 15 UFCs for Serial Production. This change was driven by the need to develop resilience in the supply chain for the production of electrodeposited coatings. In this regard, a new Vendor with expertise in the application of electrodeposition of copper coatings to cylindrical geometry was contracted for the supply of copper coated UFC shell components. In comparison to the "Reference Assembly Method" (copper coated lower assembly + copper coated upper head) the "Alternate Assembly Method" would have 3 copper coated components for assembly: lower head, shell and upper head. The Alternate Assembly Method necessitates the application of cold spray coating to both the lower and closure weld zones. A comparison between the reference assembly method and alternate assembly method is presented in Table 4-1.

The quantity of UFC components manufactured and processed in 2021 are documented in Table 4-2. The completion status at the end of 2021 of the planned total of 15 Serial Production UFCs is shown in Table 4-3, broken down by major components.

Moving forward, a significant effort will be spent in completing the remaining UFCs, targeted by the end of 2022.

Table 4-1: Reference vs. Alternate Assembly Method Comparison

Reference Assembly Method



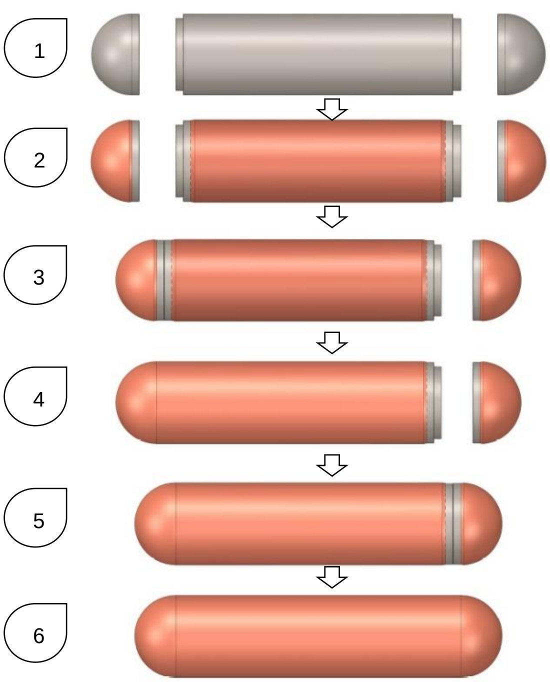
Reference Assembly Method Schematic

Steps:

1. Steel Components
   - 2 Hemi-heads
   - Shell
2. Weld Lower Assembly
3. Copper Coating
   - Lower Assembly
   - Upper Hemi-head
4. Closure Weld
5. Copper Coating over Closure Zone

Photo of Reference Assembly Method at Step 3

Alternate Assembly Method



Alternate Assembly Method Schematic

Steps:

1. Steel Components
   - 2 Hemi-heads
   - Shell
2. Copper Coating
   - Lower Hemi-head
   - Shell
   - Upper Hemi-head
3. Lower Assembly Weld
4. Copper Coating over Lower Assembly Weld
5. Closure Weld
6. Copper Coating over Closure Zone

Photo of Alternate Assembly Method at Step 2

Table 4-2: 2021 UFC Serial Production Results

UFC Component	2021 Quantity				
	Steel Machining	Welding & Weld NDE	Copper Coating	Copper Coating Machining	Copper NDE
Upper Hemi-head*	10	N/A	9	9	5
Lower Hemi-head	0	N/A	N/A	N/A	N/A
Shell	5	N/A	5	5	2
Lower Assembly	5	0	5	5	5
UFC Assembly	N/A	5	3	2	1

*Upper Hemi-heads are used as Lower Hemi-heads for the Alternate Assembly Method.

Table 4-3: 2021 UFC Serial Production Status

<table>
<tr><th colspan="5"><u>Reference Assembly Method</u></th></tr>
<tr><th>UFC No.</th><th colspan="2">Copper Lower Assembly</th><th>Copper Upper Hemi-head</th><th>UFC Assembly</th></tr>
<tr><td>1</td><td colspan="2"></td><td></td><td></td></tr>
<tr><td>2</td><td colspan="2"></td><td></td><td></td></tr>
<tr><td>3</td><td colspan="2"></td><td></td><td></td></tr>
<tr><td>4</td><td colspan="2"></td><td></td><td></td></tr>
<tr><td>5</td><td colspan="2"></td><td></td><td></td></tr>
<tr><td>6</td><td colspan="2"></td><td></td><td></td></tr>
<tr><td>7</td><td colspan="2"></td><td></td><td></td></tr>
<tr><td>8</td><td colspan="2"></td><td></td><td></td></tr>
<tr><td>9</td><td colspan="2"></td><td></td><td></td></tr>
<tr><td>10</td><td colspan="2"></td><td></td><td></td></tr>
<tr><th colspan="5"><u>Alternate Assembly Method</u></th></tr>
<tr><th>UFC No.</th><th>Copper Lower Hemi-head</th><th>Copper Shell</th><th>Copper Upper Hemi-head</th><th>UFC Assembly</th></tr>
<tr><td>11</td><td></td><td></td><td></td><td></td></tr>
<tr><td>12</td><td></td><td></td><td></td><td></td></tr>
<tr><td>13</td><td></td><td></td><td></td><td></td></tr>
<tr><td>14</td><td></td><td></td><td></td><td></td></tr>
<tr><td>15</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="5"></td></tr>
<tr><th colspan="2">Legend</th><td>Completed</td><td>In Process</td><td>Not Started</td></tr>
<tr><th colspan="2">Definitions</th><td>All work complete.</td><td>Work has started on the base material or assembly.</td><td>Work has not started on the base material or assembly.</td></tr>
</table>

4.1.3 UFC Copper Coating Development

4.1.3.1 Electrodeposition Process Development

Since the inception of this work, the NWMO has engaged prime contractor Integran Technologies, Inc. (Integran, Mississauga, Ontario, Canada) to develop a copper electrodeposition technology for application to UFC components (i.e., upper hemi-heads and lower assemblies).

(a) **(b)**

Figure 4-3: Upper Hemi-head Serial Production (a) Entry Into Plating Tank and (b) Finished Product Ready for Post-plating Machining

A recent initiative (2020) was pursued to evaluate and implement a more robust copper electrodeposition system by substituting the prior pyrophosphate-based chemistry with a copper sulfate/sulfuric acid-based chemistry also known as “acid copper” along with a pulse-reverse applied current. In 2020, early-stage developments were initiated leading to a copper material that was sufficiently pure (> 99.9%) and ductile (> 10% elongation). At that point, it was decided to pursue scale-up to UFC components. With extensive optimization, the process was demonstrated to be scalable and soon after implemented in serial production. During 2021, nine upper hemi-heads (Figure 4-3) and five lower assemblies (Figure 4-4) were successfully produced and submitted for final machining and non-destructive examination.

(a) (b)

Figure 4-4: Lower Assembly Serial Production (a) Removal from Plating Tank and (b) Finished Product Ready for Post-machining

In parallel to the resumption of serial production activities in 2021, further laboratory scale process optimization was performed with the following objectives:

1. Determine process tolerances in an effort to establish operating ranges for parameters such as chemistry, temperature, and current density;
2. Improve the purity of the material such that NWMO specifications are satisfied for oxygen, phosphorus, hydrogen, carbon, and sulfur; and,
3. Improve the ductility of the copper material to a target of >20% elongation.

For items (1) and (2), primary focus was given to the control of organic additives in the system since they are known to strongly affect microstructure and purity. This work made use of analytical chemistry equipment that would be used study the rate of consumption and eventually determine the concentration range and replenishment frequency that would provide for optimal microstructure and purity. Temperature was also found to affect microstructure and purity while a lower effective current density was found to produce a smoother deposit. When combining the effects of organic additive concentration and temperature, ranges were determined which produced the microstructures shown in Figure 4-5.

By observation, the microstructure was also determined to be fully dense, showing no signs of porosity. After producing a series of samples with the fixed chemistry, temperature, and current density conditions, the microstructure was found to be consistently reproducible. Purity also met the current reference specifications (Table 4-4).

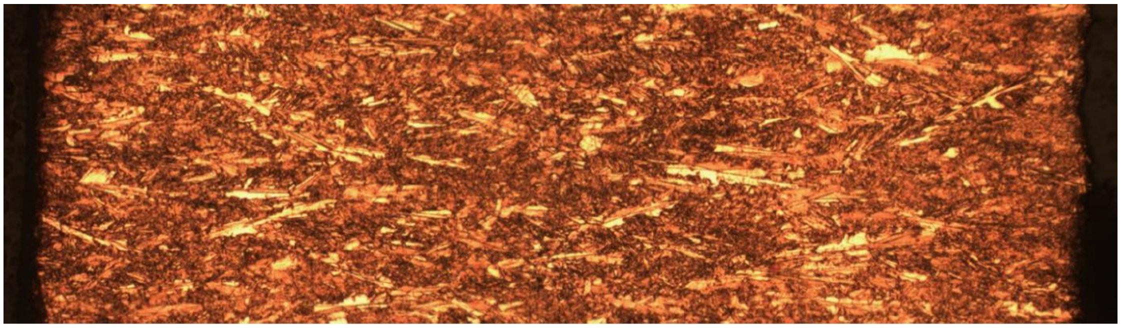


Figure 4-5: Through Thickness Microstructure from Substrate (left to right) Showing a Mixture of Both Elongated and Fine Grains

Table 4-4: Purity Results from Optimized Process Chemistry, Temperature, and Current Density

Sample No.	Cu (> 99.9 %)	S (<0.0012 %)	P (<0.010 %)	C (<0.005 %)	O (<0.010 %)	H (<0.0010 %)
1	>99.9	<0.0012	<0.005	<0.001	0.001	0.0002
2	>99.9	<0.0012	<0.005	<0.001	0.001	0.0001
3	>99.9	<0.0012	<0.005	<0.001	0.001	0.0001

To complete an assessment of the refined processing parameters, a series of tensile tests were performed to determine the yield strength, ultimate tensile strength and most importantly ductility (i.e., % elongation).

At the conclusion of 2021, the laboratory scale process optimization work was completed, and the objectives met. In early 2022, the refined process parameters will be scaled and further trialed in the production tanks on a coupon level using the current production tanks. Following confirmation of scalability, the newly refined process will be implemented at the UFC component level (i.e., upper hemi-heads and lower assemblies) to complete the remainder of the serial production campaign at Integran.

Figure 4-6 provides an image of the tensile specimens and a representative stress-strain curve. Table 4-5 provides the results of the tests.

Table 4-5: Tensile Testing Results with Requirements

Sample No.	Yield Strength (>60 MPa)	Ultimate Tensile Strength (>220 MPa)	Elongation (>10 %)
1	118	283	21
2	154	285	21
3	115	276	20

At the conclusion of 2021, the laboratory scale process optimization work was completed, and the objectives met. In early 2022, the refined process parameters will be scaled and further trialed in the production tanks on a coupon level using the current production tanks. Following confirmation of scalability, the newly refined process will be implemented at the UFC component level (i.e., upper hemi-heads and lower assemblies) to complete the remainder of the serial production campaign at Integran.

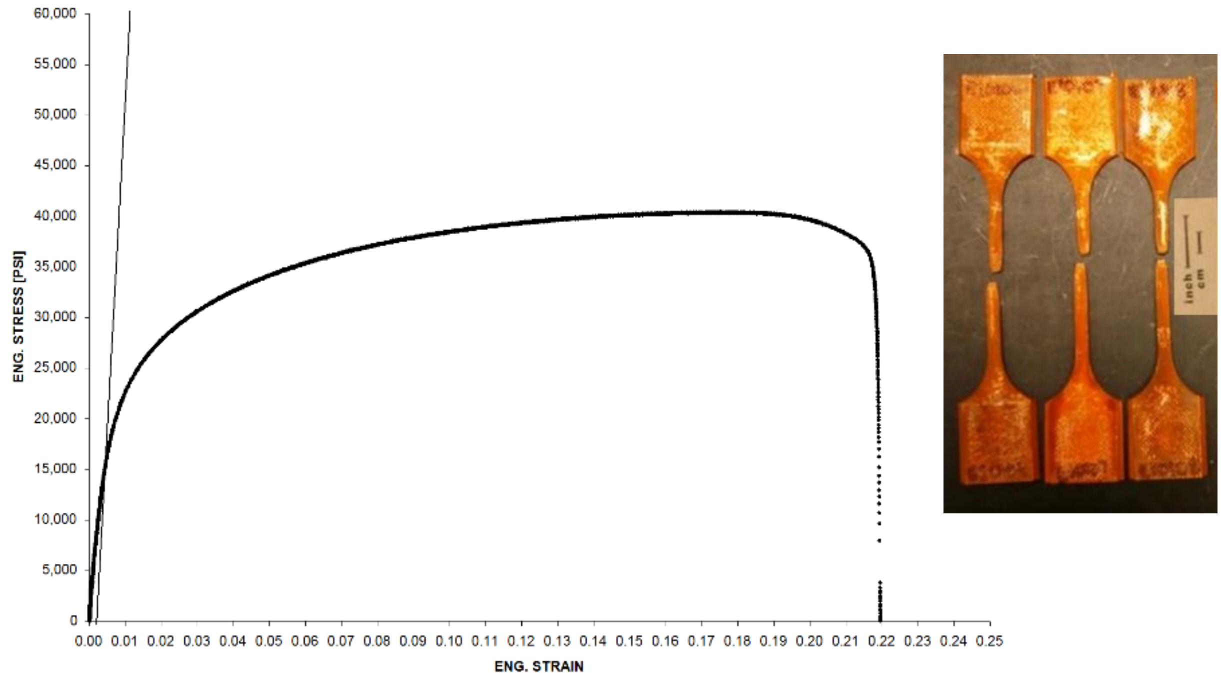


Figure 4-6: Tensile Testing (left) Stress-Strain Curve and (right) Specimens After Fracture

As described in Section 4.1.2.1, an initiative to assess an alternate commercial electrodeposition method for the supply of copper coated UFC shells was launched in 2021. For this work, BEP Surface Technologies, Ltd. (BEP, Manchester, UK) was contracted to qualify their copper coating material produced by an acid electrodeposition process. In the qualification trial, BEP was able to achieve the NWMO's material performance (i.e., purity, adhesion, and ductility) and quality (i.e., non-destructive examination) requirements. Subsequently, BEP was released to copper coat UFC serial production shells. The shells were delivered in 2021 for final machining and assembly. Figure 4-7 shows an example of a copper coated (pre-machined) UFC shell delivered to the NWMO.

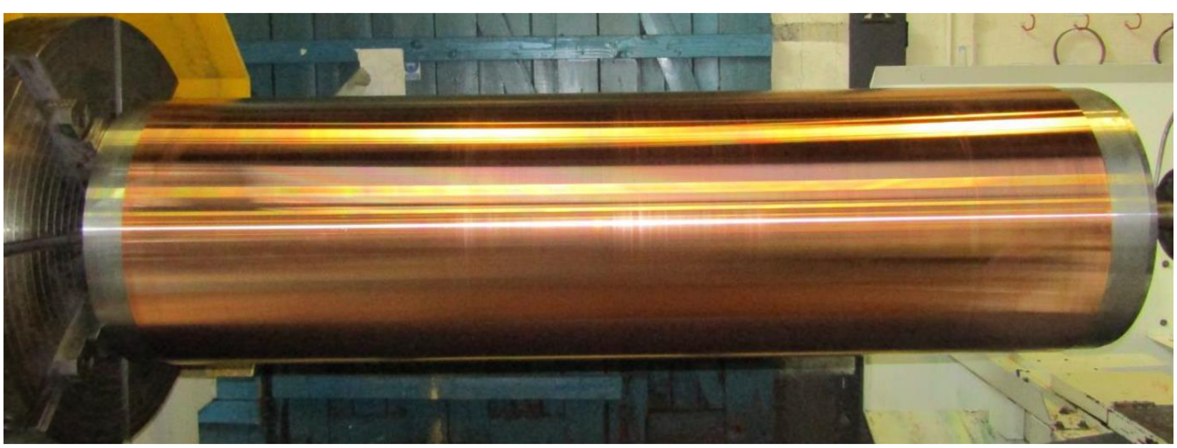


Figure 4-7: Copper Coating UFC Shell Component by Electrodeposition and Pre-machined by BEP Surface Technologies (BEP, Manchester, UK)

4.1.3.2 Cold Spray Process Development

The NWMO has engaged with the National Research Council Canada (NRC, Boucherville, QC) to develop a cold spray copper coating technology since 2012. In 2020, several advanced techniques were developed and scaled. At the conclusion of this work, a reference copper cold spray process was established and deemed ready for implementation in a production environment. The facility selected for the serial production campaign and thus, implementation of the reference copper cold spray process was the newly constructed PolyCSAM Industrialization Centre (Boucherville, QC) located within the NRC facilities and operated by Polycontrols, Inc. (Brossard, QC). Efforts to implement the reference process were initiated in 2021 leading to a full process qualification and demonstration that was completed in the later part of 2021 followed by the start of serial production.

Implementation of the reference process included primarily the task of transferring the know-how and advanced techniques by adapting them to the equipment at the PolyCSAM Industrialization Centre. The specific process qualification and demonstration activities consisted primarily of the following:

1. Production of cold sprayed copper coatings on “pipe segments” of equivalent diameter to the UFC and testing to qualify the process (e.g., microstructural analysis, adhesion, and ductility via tensile testing).
2. Production of cold sprayed copper coating on a UFC component (i.e., lower assembly) using the NWMO’s issued rotational equipment for UFC’s and testing to qualify the process (e.g., adhesion and ductility assessment via hardness testing); and,
3. Demonstration trial to apply a cold sprayed copper coating to the closure weld zone of a UFC.

For (1), several trials were performed on the pipe segments while adapting know-how to the equipment and examining the resulting cold sprayed material for key indicators of an acceptable material performance [i.e., hardness, ductility (% elongation), and adhesion strength]. Figure 4-8 to Figure 4-11 provide some images of the qualification / demonstration steps at scale on a sequence of substrates, namely a pipe segment, lower assembly, and demonstration UFC, respectively. In all three cases, the main steps to produce the coating were as follows:

1. Laser ablation to remove residual oxides/scale from the surface.
2. Bond layer application using laser assistance and nitrogen carrier gas; and,
3. Thickness build-up using nitrogen carrier gas.

The heat treatments for the three different cases were not all the same. In the case of the pipe segment, samples were extracted, and heat treated in a furnace while for the lower assembly and UFC, the band heat treatment method was used. Further details are provided in Table 4-6.

Table 4-6: Results from Qualification / Demonstration Trials with Requirements

Substrate	Surface Hardness (< 280 HLD)	Microhardness (< 66 $HV_{0.300}$)	Elongation (> 10 %)	Adhesion Strength (> 20 MPa)
Pipe Segment	233±9	63±2	33.2±1.3	67±5
Lower Assembly	206±12	61±1	N/A	67±6
UFC	209±15	N/A	N/A	N/A

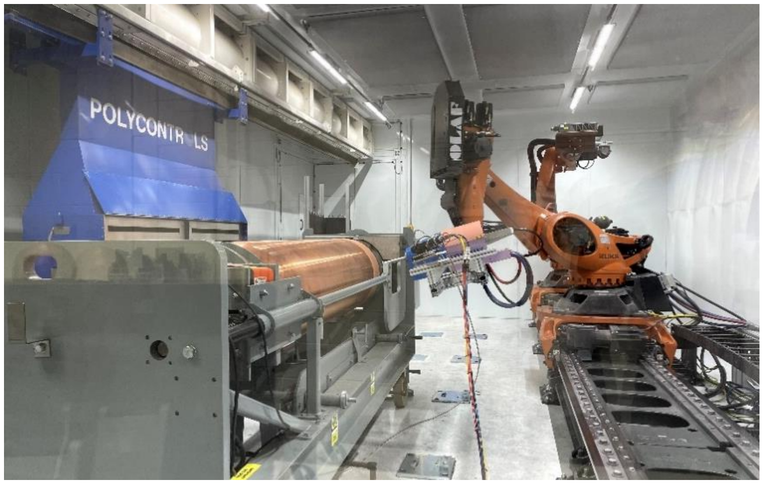
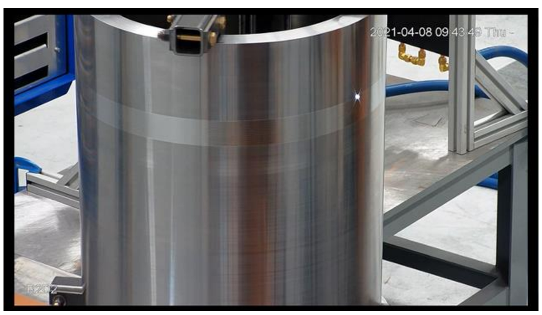
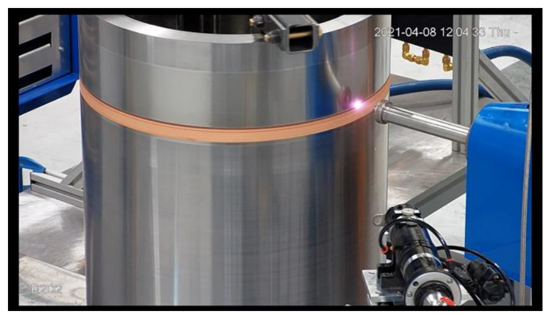


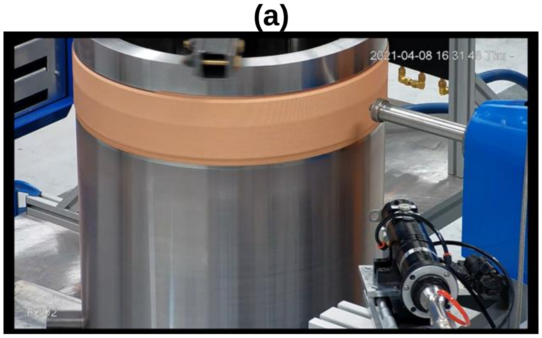
Figure 4-8: PolyCSAM Industrialization Centre (Boucherville, QC): UFC in Rotating Equipment Undergoing Cold Spray Operation to Build-up Thickness



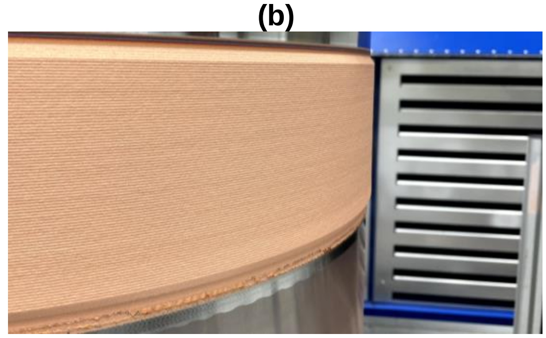
(a)



(b)



(c)



(d)

Figure 4-9: Qualification Trial with Pipe Segment: (a) Laser Ablation, (b) Bond Layer Application, (c) Thickness Build-up, and (d) Final Coating Ready for Furnace Heat Treatment After Sample Extraction

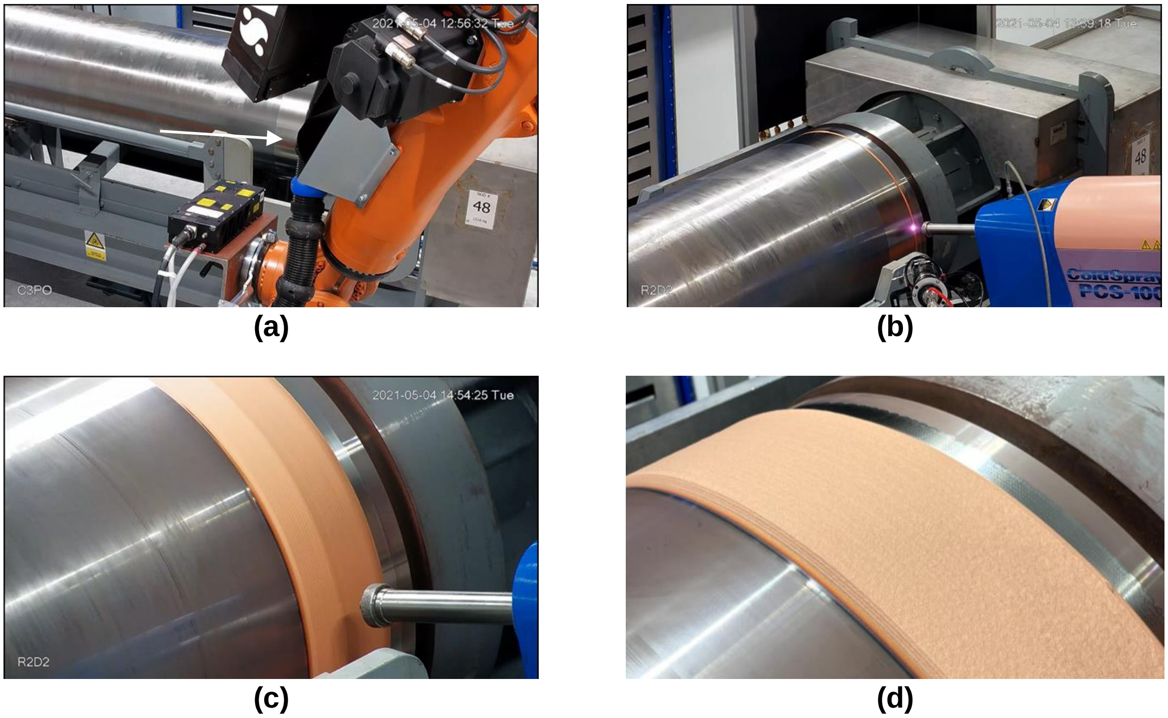


Figure 4-10: Qualification trial with lower assembly: (a) laser ablation, (b) bond layer application, (c) thickness build-up, and (d) final coating ready for band heat treatment.

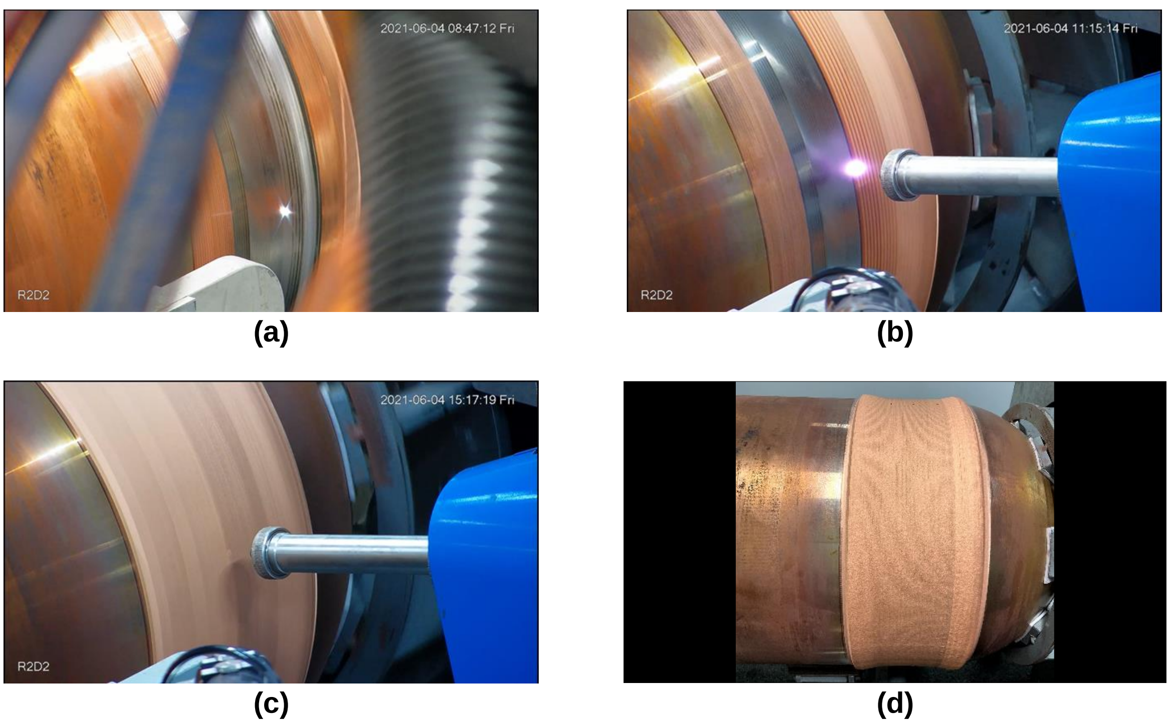


Figure 4-11: Demonstration Trial with UFC: (a) Laser Ablation, (b) Bond Layer Application, (c) Thickness Build-up, and (d) Final Coating Ready for Band Heat Treatment

In previous work, a relationship between hardness and % elongation was established as a means to obtain an indirect assessment of ductility for quality assurance purposes after applying a heat treatment to the coating. Surface hardness (HLD or Leeb rebound hardness with spherical impact body) is used in the case where destructive testing is not permitted, i.e., for quality control of the final product. On the other hand, microhardness (Vickers) is used where destructive testing is permitted. For the pipe segment, both hardness measurements met the NWMO's reference specifications correlating to acceptable ductility following a furnace heat treatment. The lower assembly also provided acceptable hardness values following a band heat treatment method. For the UFC, after several trials and optimization of the band heat treatment method, an acceptable surface hardness value was achieved. Adhesion strength, where destructive testing was permitted (i.e., pipe segment and lower assembly), was found to be well in excess of the minimum requirement.

With these results from the qualification and demonstration trials, the reference process was deemed to be ready for the serial production campaign. In late 2021, the application of cold spray copper coating to the closure zone of three UFC's was completed; these vessels were subsequently submitted for final machining and non-destructive examination to complete the fabrication process. In 2022, it is planned to complete the remaining UFC closure weld zone coating serial production campaign.

4.1.3.3 Technical Research on Copper Coating Materials

In 2021, technical research with focus on the characterization of the copper coating materials was further advanced in partnership with the University of Toronto (Toronto, ON). One journal article released in 2021 entitled *"The Effect of Annealing on Trapped Copper Oxides in Particle-Particle Interfaces of Cold Sprayed Cu Coatings"* was published (Tam et al., 2022).

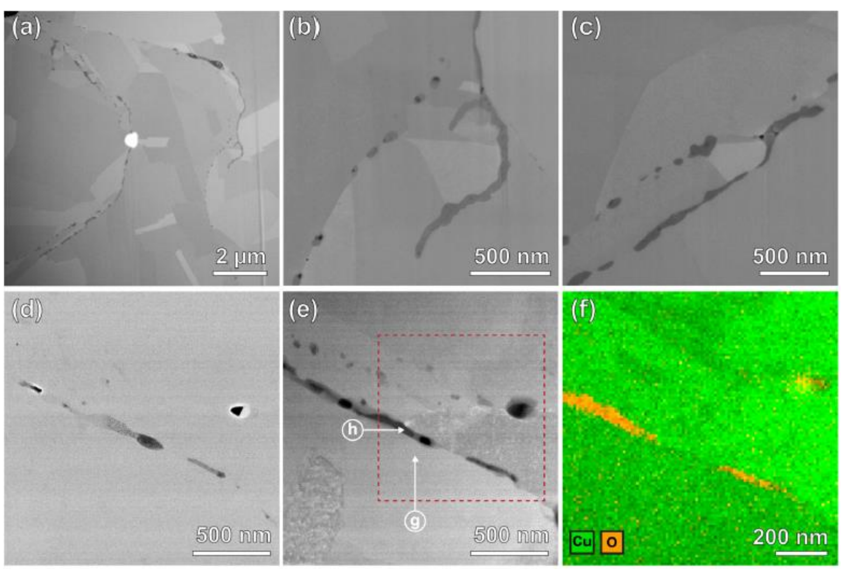


Figure 4-12: Example Image Analysis from Cited Publication (Tam et al., 2022): Microstructure, Phase, and Chemical Analysis of Cold-sprayed Cu Coating after Annealing at 350° C for 1 h. (a - d) SE Images, Showing Particle-particle Interfaces with Discontinuous Fragments of Copper Oxides. (e) HAADF Image. (f) EELS Map, Showing the Spatial Distribution of Cu and O in the Region Marked in (e).

This work focused on the evolution of oxides in cold sprayed copper coatings after annealing treatments with insight into the mechanisms leading to enhanced ductility. Characterization of the material was performed using scanning electron microscopy (SEM) and transmission electron microscopy (TEM) as in Figure 4-12. The material was analyzed in the “as-sprayed” state (i.e., no annealing treatment), annealed at 350°C and 600°C. The main finding was that with increasing annealing temperature, the copper oxides lining particle-particle interfaces break up and coarsen, leading to an increase of metallurgical bonding. With increased metallurgical bonding, ductility enhancement can also be expected.

4.1.4 UFC Copper Components Machining

The UFC components which are copper coated by electrodeposition (shell, hemi-head, lower assembly and cold spray weld (closure zone) processes are generally uneven in the as-deposited condition. Post-deposition machining is performed to bring the coating thickness into dimensional compliance and to prepare the surface for inspection via non-destructive examination techniques. The machining is carried out in accordance with detailed manufacturing, inspection and testing plans and procedures. Table 4-7 shows pictures of each component as it moves from as-machined steel condition though copper coating and final machining.

In 2021, progress was made in developing the final machining operation applied to the UFC. After the closure weld and closure zone cold spray copper coating are completed, the copper in the closure zone must be machined and blended to match the surrounding copper surfaces on either side (cylindrical surface of the Copper Coated Lower Assembly and spherical surface of the Copper Coated Upper Hemi-head).

Table 4-7: UFC Copper Coated Components Stages of Manufacture

UFC Component	Copper Coating Stages		
	Steel	Bulk Copper	Machined Copper
Hemi-head			
Shell			
Lower Assembly			
Closure Zone			

The machining diameter and radius are based on the measured actual dimensions of each unique UFC. The copper coating applied by the cold spray process is applied with a 1mm offset from the surrounding surfaces which provides adequate machining allowance. After machining, blending is required since the Lower Assembly and Upper Hemi-head are likely to have offset centrelines at the time of assembly and offset between mating surface and copper machining surface centrelines on each component. It is not feasible to machine a profile that would conform to the exact shape and size combinations that would exist, therefore a blending operation has been employed to smooth these transitions. The blending also serves to smooth the machined surfaces which may be rougher than desired due to the method of machining being horizontal milling with a long extension bar, especially on the spherical surface. Smoother surfaces are desired to support subsequent NDE operations.

4.1.5 UFC Non-Destructive Examination

The UFC is inspected for fabrication and material flaws using non-destructive examination (NDE) methods at multiple stages of the manufacturing process. Ultrasonic testing and eddy current testing are used to detect volumetric and surface flaws, respectively, in the UFC steel structural vessel and copper coating.

In 2021, the Non-Destructive Examination (NDE) program focused on application of equipment upgrades to perform inspection of copper coated UFC components. Mechanized systems for copper coated component NDE were developed, manufactured, and commissioned in 2020. The mechanized systems improved repeatability and data quality of the inspections. And inspection times were reduced by approximately 15%. The scanning mechanisms attach to the NDE inspection benches as shown in Figure 4-13 (hemi-head scanning mechanism) and Figure 4-14 (lower assembly/UFC scanning mechanism). The scanning mechanisms were used for Serial Production copper coating inspections in 2021 on 4 hemi-heads, 2 shell sections, 5 lower assemblies, and 2 closure zones.

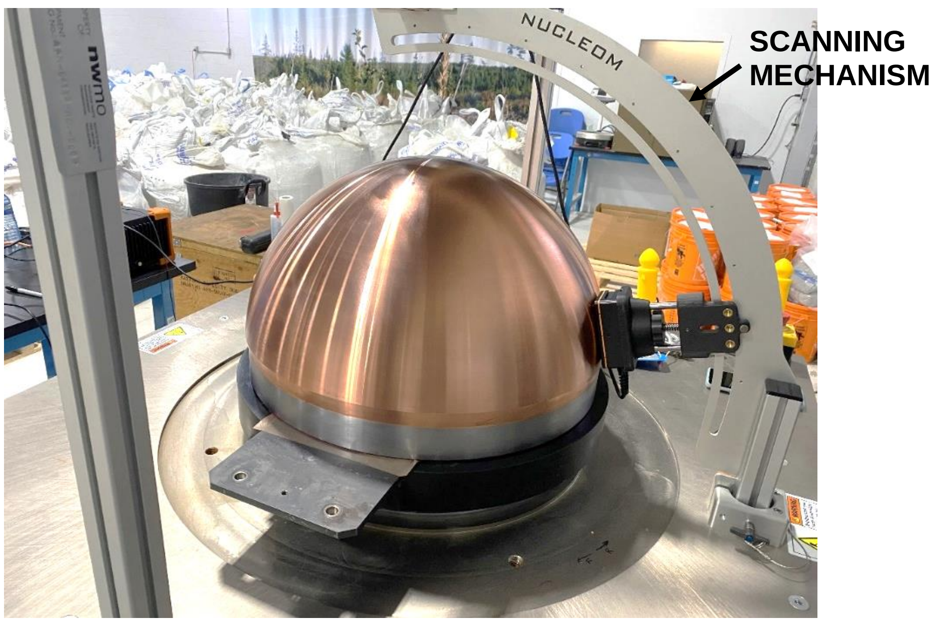


Figure 4-13: Hemi-head Scanning Mechanism with Eddy Current Probe Attached, During Inspection of Copper Coated Upper Hemi-Head

Figure 4-14: Lower Assembly/Used Fuel Container (UFC) Scanning Mechanism with Ultrasonic Probe Attached During Inspection of Closure Zone

4.1.6 UFC Material Testing

In 2021, NWMO's vendor, Cambridge Materials Testing Limited (Cambridge, ON), completed the advanced mechanical testing project for the UFC carbon steel materials. The testing project was intended to collect mechanical properties of the material in the weld and the heat affected zones, including tensile strength and impact toughness. The testing was also designed to obtain strain hardening information of the base and weld metals beyond the ultimate strength. The testing included non-standard tensile tests and Charpy V-notch impact tests.

A set of non-standard tensile tests were conducted at the room and elevated temperatures to establish the true stress-strain curves up to rupture of the base and weld materials as documented in Figure 4-15. The portion beyond the ultimate strength point of such a curve was obtained with the help of a laser speckle extensometer. The true stress-strain curves contain detailed information on the materials' behavior subjected to very large plastic deformation. This allows accurate computer modeling of UFC response to the beyond design basis conditions, such as plastic collapse due to excessive external pressure or rupture due to high shear force caused by rock movement. Moreover, the true stress-strain curves also provide information on the ductility of the materials, which would allow the strain-based design criteria in ASME BPVC Section III Division 3 to be applied for energy limited events (e.g., drop, impact and displacement driven events).

The Charpy V-notch impact tests were conducted for the UFC steel base and weld materials to establish the ductile-to-brittle transition curves. These curves shown in Figure 4-16 provide information on impact toughness of the materials and the ductile-to-brittle transition temperature (DBTT) below which the carbon steel rapidly loses its ductility. The impact toughness and the DBTT are important properties to determine the lowest service temperature of the UFC and the strength of the UFC against impact loads, such as in a drop event.

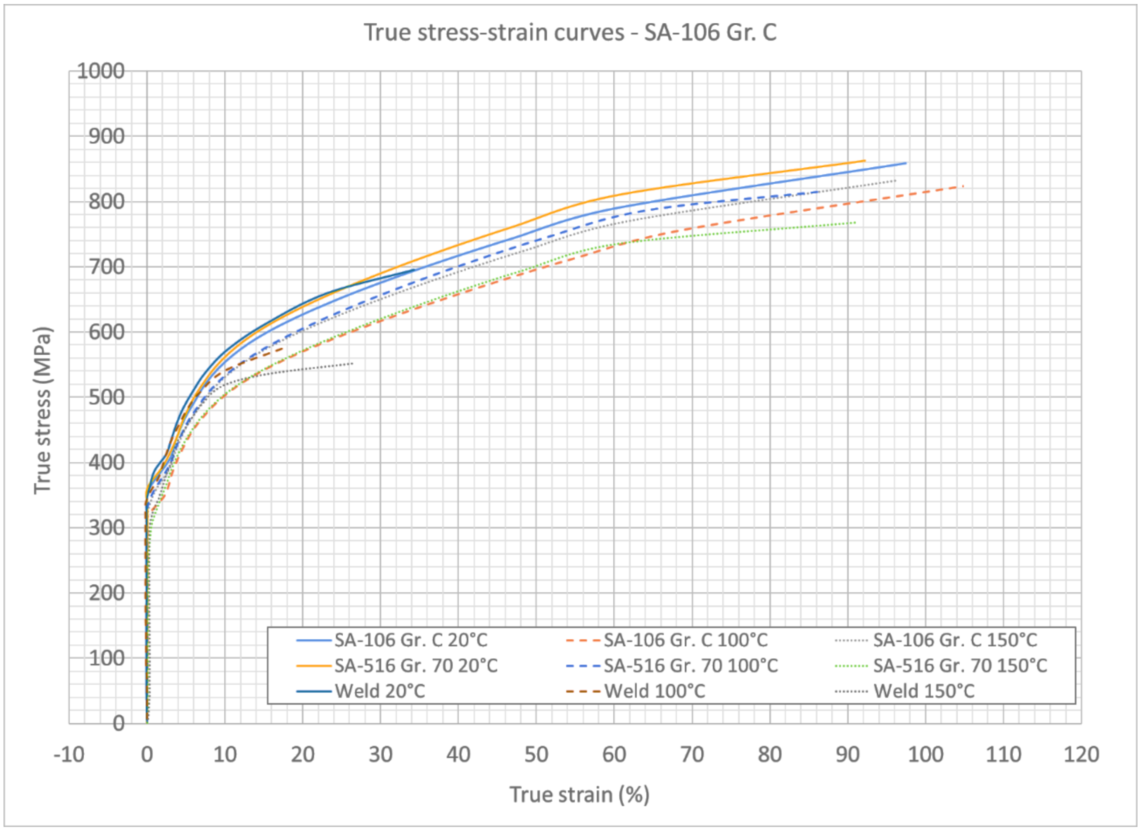


Figure 4-15: True Stress-strain Curves up to Rupture of the UFC Steel Materials at Various Temperatures

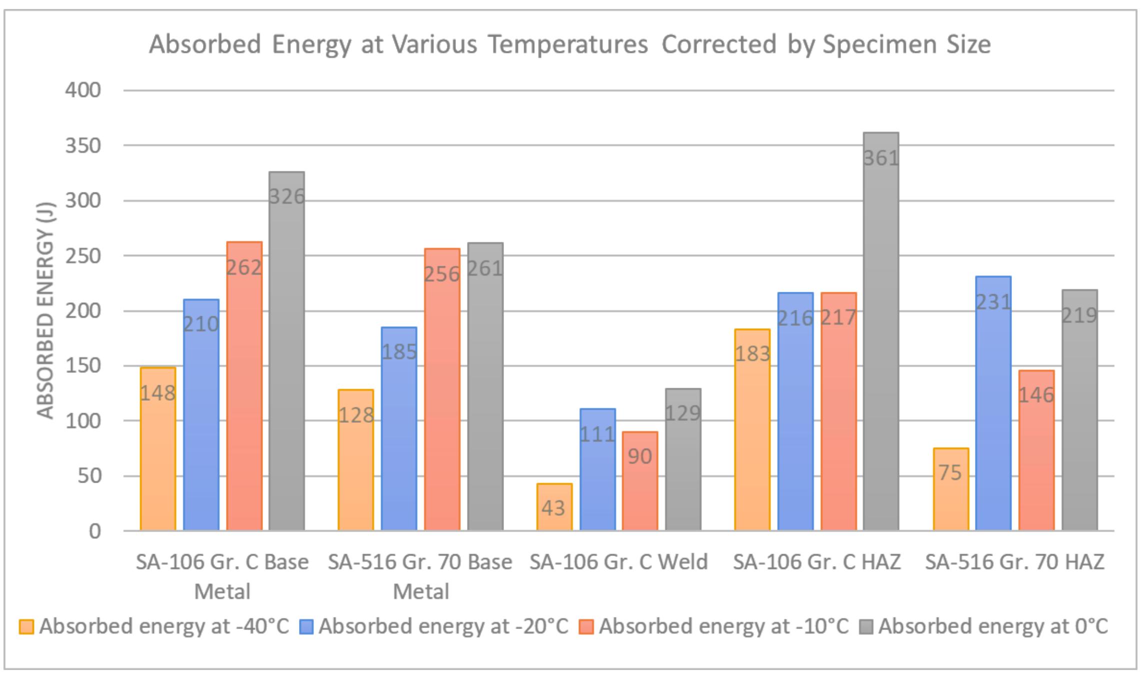


Figure 4-16: Average Absorbed Impact Energy at Various Temperatures

4.2 COPPER DURABILITY

4.2.1 Used Fuel Container Corrosion Studies

4.2.1.1 Anoxic Corrosion of Copper

Following closure of the DGR, oxygen will be present for a short period of time. However, this oxygen will be consumed by mineral reactions, aerobic microbial metabolism and corrosion leading to a highly reducing environment for the majority of the DGR's lifetime. The absence of oxygen creates an environment in which copper, the corrosion barrier of the UFC, is thermodynamically immune to corrosion provided that the pH of the groundwater does not reach extreme low values, which is not anticipated. However, while Canadian groundwaters are very low in bisulfide concentration, if sulfide reducing bacteria are present in the vicinity of the DGR it is possible that bisulfide could be created and diffuse to the UFC causing copper corrosion. While the presence of compacted bentonite in the DGR virtually eliminates this possibility, the effects of bisulfide on the integrity of the UFC and the quantification of any such corrosion is important to understand. Additionally, since there remain two potential host sites for the Canadian DGR, the specific groundwater chemistry of each site must be investigated in conjunction with the effect of bisulfide. With respect to corrosion, the dominant species in each case is chloride which is being studied at various concentrations in conjunction with bisulfide.

Work being conducted by NWMO at CanmetMATERIALS (Hamilton, Canada) in collaboration with the University of Toronto investigates the individual and the combined effects of bisulfide and chloride along with pH effects. This work utilizes a specialized corrosion cell, depicted in Figure 4-17 (a), which maintains an anoxic environment at 75 °C while allowing for the introduction of chemical species (gas or liquid) into the cell. A detailed description of this apparatus was published by Senior et al. (2020a) in 2020. Hydrogen is measured by purging the headspace of the cell and the amount is correlated to a rate of corrosion by assuming that all hydrogen production is a product of a corrosion reaction. Notably, the release of trapped hydrogen from within the copper, or the production of hydrogen from other corrosion reactions within the cell (i.e., through the interaction of steels and water) will be assumed to be copper corrosion using this calculation method, and this will overestimate copper corrosion (Senior et al. 2019). Similarly, hydrogen produced via corrosion that is absorbed by the metal will be missed in a corrosion calculation, although this process is not expected. Nonetheless, a representative graph of the results is shown in Figure 4-17 (b) which plots the cumulative hydrogen measured along with the calculated corrosion rate versus time for electrodeposited, cold sprayed and junction (i.e., cold spray overlapping electrodeposited copper) in a simulated groundwater solution which is representative of the groundwater anticipated to exist at a potential DGR host site. These cells are relatively new (~1.5 years running) to the program and showing extremely low corrosion rates (sub nm/year) as anticipated. In the coming year, these cells will be dosed with hydrogen sulfide and monitored.

The corrosion experiments are ongoing, but some consistent trends are exhibited by the data following the approximately five-and-a-half-year duration of the program. In pure water, hydrogen was evolved, and initial corrosion rates were calculated to be less than 0.5 nm/year before falling below the detection limit of the experiment. Similar results were seen for dilute and strong chloride solutions; that is, an initial small release of hydrogen followed by a gradual decline with time to near or below the detection limit. Upon addition of small concentrations of H_2S to each cell, which simulates the effects of microbially produced sulfide species, small initial releases of hydrogen are observed followed by a return to corrosion rates which near the detection limit of the hydrogen probe. It is also important to note that each cell underwent integrity and leak testing at the end of 2019 to ensure that hydrogen was not escaping the cells. These tests will continue with additional spiking of H_2S gas, altering electrolyte pH, and increasing chloride concentrations to investigate the behaviour of the copper. When complete, test cells will be disassembled and the copper interrogated for the presence of absorbed hydrogen and the makeup of corrosion products which is anticipated to begin in 2022. More detailed results from this program have been published by Senior et al. (2019) and (2020b).

As mentioned above, the introduction of sulfide to either saline or pure water environments did result in hydrogen evolution, producing initial low corrosion rates equivalent to 0.1 and 0.2 nm/year, respectively, which drop to the detection limit of the experiment over several months. However, even if for a damage assessment, it was assumed these rates were sustained, the largest of these miniscule rates would produce less than 0.25 mm of damage in 1,000,000 years and are consistent with the conservative NWMO total corrosion allowance of 1.204 mm over that period of time (Hall et al. 2021).

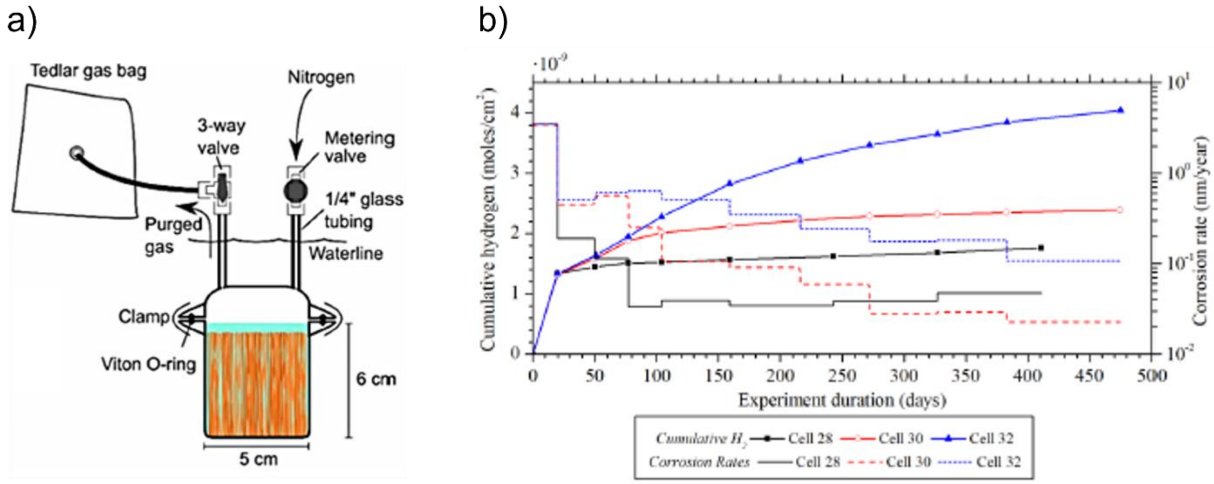


Figure 4-17: (a) Schematic of Test Cells for Anoxic Copper Corrosion Investigations at CanmetMATERIALS; (b) Cumulative measured Hydrogen and Calculated Copper Corrosion Rates for Three Cells Containing Cold Spray, Electrodeposited, and Junction Material, all in Simulated Canadian Groundwater Versus Time

4.2.1.2 Corrosion of Copper Coatings

Since 2019, the NWMO has been focusing on identifying or narrowing the chemistry requirements for copper coatings with an intent to create a purity specification for copper coatings that emphasizes corrosion performance. The purity specification of copper coatings includes trace chemical species (metallic and non-metallic) that may be incorporated into the coating during the manufacturing process. Based on an extensive literature review, amongst the non-metallic impurities possible to be present in copper coating, oxygen was identified to have an impact on the copper corrosion under certain environments. Experimental studies including both electrochemical measurements and surface analysis have been performed to investigate the role of oxygen on corrosion behaviour of selected commercial and customized copper alloys under both aggressive and non-aggressive conditions. Based on the initial phase of assessment, it is concluded that although short term aggressive conditions induced more corrosion on oxygen containing copper alloys, this has not been observed to exceed the localized corrosion allowance of 100 µm (Hall et al. 2021). It should be noted that the aggressive conditions used in these experiments are not expected in a repository, therefore, the maximum damage observed on these samples is still conservative. Further experimental work is underway to determine the concentration limits of the individual constituents by which the reference (wrought) corrosion allowance can be maintained.

4.2.1.3 Galvanic Corrosion of Carbon Steel in the Presence of Bentonite

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

Previous work revealed that the extent of galvanic corrosion of CS is highly sensitive to O_2 availability and salinity and that abundant O_2 and high salinity could result in aggressive corrosion of the carbon steel (Standish et al. 2016, 2018, 2019). However, the short period of oxic phase along with the presence of highly compacted bentonite in a DGR are expected to limit the extent of galvanic corrosion. To support this prediction, the galvanic corrosion of CS coupled to copper was investigated in the absence and presence of Na-based bentonite clay saturated with 1 M NaCl solution under aerated and de-aerated conditions. Layers of bentonite slurry of various thicknesses were made to obstruct galvanically coupled Cu and CS specimens in order to determine how, and the degree to which, clay suppresses galvanic corrosion, separate from its swelling pressure and low hydraulic conductivity. Results from this study showed that the addition of bentonite clay produced benign corrosion conditions by limiting the reduction of O_2 on Cu, thereby decreasing the oxidation of CS. This work presented a conservative case that even with extremely low bentonite density, high conductivity, large Cu:CS area ratio, and an unlimited supply of O_f, the galvanic corrosion of CS was slowed significantly compared to that in the absence of bentonite. To conclude, in a DGR the galvanic corrosion that could occur at a through-coating defect would be greatly hindered by the presence of the highly compacted bentonite clay encasement, which would represent a much more formidable barrier than the loose slurry employed in these experiments.

4.2.1.4 Corrosion of Copper in Radiolytic Environment

The copper coated UFC will be exposed to a continuous flux of γ-radiation emitted from the decay of radionuclides in the used fuel. Although the γ-radiation does not affect the metal directly, any trapped water or humid air near the UFC will decompose to produce redox-active and acidic species that can affect the corrosion of the copper coating.

In addition to fundamental and mechanistic studies underway to understand the copper corrosion behaviour in the presence of γ-radiation, new results have been obtained from examinations of irradiated copper surfaces that were exposed to about 40 years of gamma and neutron radiation in National Research Universal (NRU) reactor (Turnbull et al. 2022). Based on the results obtained in this work, it’s evident that long term gamma and neutron irradiation of copper at dose rate of 0.015 Gy/h after 40 years (total dose of 4880 Gy) in humid air environment (~ 40 °C) did not induce substantial corrosion damage on copper surface, Figure 4-18.

The hardness measurements were also performed with a 100-g load of the cross section on both irradiated and non-irradiated copper surfaces. An analysis of the microhardness concluded that negligible irradiation hardening occurred to the irradiated Cu surface despite the constant flux of neutron and gamma irradiation during the operation of the research reactor. These results add further supporting evidence on the longevity and integrity of Cu when exposed to long term gamma radiation.

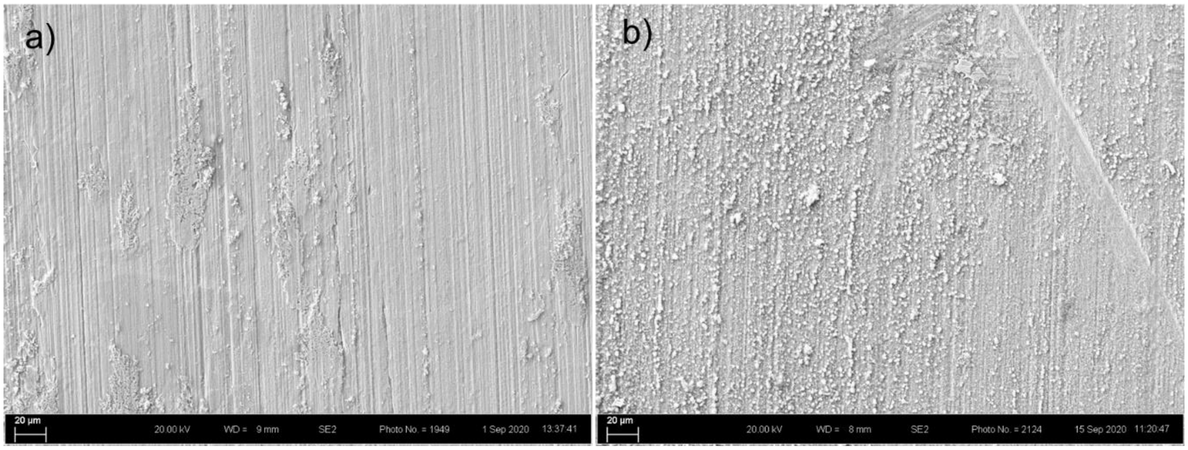


Figure 4-18: Representative Scanning Electron Microscope Micrographs of the Interior Surface of the Non-irradiated Cu Pipe (a) and the Irradiated Cu Pipe (b).

4.2.1.5 Natural Analogue to Support the Prediction of Copper Corrosion Behaviour

Natural analogues are useful supporting evidence for the prediction of the long-term corrosion behaviour of used fuel containers (UFC). Evidence from analogues can be used for a number of purposes, including to support the development of conceptual models for long-term performance, the validation of mechanistically based corrosion models, the provision of corrosion damage data (typically either corrosion rates or measurements of localized corrosion) over long exposure periods, or generally to build confidence in long-term predictions (King 2021).

As part of a new collaborative project funded by NSERC and NWMO, Western University initiated a task to locate, observe, and acquire natural Cu specimens and perform characterization and corrosion testing. The current plan is to have two excursions to conduct field work. The first will be a trip to the Keweenawan Peninsula of Northern Michigan to investigate natural Cu deposits at the surface, and the second will be to examine occurrences of natural Cu in bedrock north of Sault Ste. Marie and undertake Indigenous community engagement in the Sault Ste. Marie region. Researchers at Western University also have conditional permission to access commercial drill core sheds in the Sault Ste. Marie region to seek and retrieve specimens from Cu deposits found at depths of ~900 m. The goal is to target Cu deposits both at the surface and the depth. Selection of specimens will also be guided by the findings of the Michigan International Copper Analogue (MICA) Project, a collaboration of the Geological Survey of Finland, NWMO, SKB, Nagra, and RWM that will run in parallel to this project and will identify natural Cu materials that have been altered by specific geological processes.

4.2.2 Internal Corrosion of the UFC

The nature of the environment inside the UFC has been described by Wu et al. (2019). Although the radiation fields are higher on the inside of the container, any effect on the corrosion of the C-steel vessel is limited by the availability of H_2O. Wu et al. (2019) considered various scenarios based on whether or not the UFC internal void space was inerted with Ar during sealing and whether any fuel pencils were water-logged due to incomplete drying prior to encapsulation. Between zero and 2.2 mol O_2(g) and between 0.34 and 4.5 mol H_2O were considered in the various scenarios. The conclusion from the analysis was that due in part to the limited inventories of O_2 and H_2O, there is negligible risk from general corrosion, pitting, crevice, corrosion, or stress corrosion cracking of the closure weld. In addition, the fast neutron fluence was insufficient to cause radiation embrittlement of the C-steel vessel.

To complement the mass balance analysis and previous experimental studies (Wu et al. 2017, Guo et al. 2020a,b), development of a quantitative rate model for C-steel corrosion is underway as a function of solution parameters over the ranges anticipated inside the UFC. In parallel, further experimental studies are ongoing to build a database on C-steel corrosion as a function of solution conditions. The database will be used to extract the values of rate parameters for the rate and flux equations included in the model during model development, and to provide data for model validation and refinement.

4.2.3 Microbial Studies

The design of the repository emplacement room utilizes HCB to suppress microbiological activity near the UFC. However, as microbiological activity may occur within bentonite that is improperly placed, as well as elsewhere underground, considerable efforts are being made to study it. Recent work has focused specifically on extraction and characterization of the DNA held within the bentonite clay, as this material is present in extremely low quantities (Engel et al. 2019a, Vachon et al. 2021). Much of this work is conducted in concert with corrosion and bentonite programs, as well as within work that is performed at the underground research laboratories (Mont Terri and Grimsel) in Switzerland (Engel et al. 2019b,).

To supplement the in-situ work being performed in underground labs, pressure vessels (Figure 4-19(a)) have also been designed, fabricated and commissioned to perform a large number of ex-situ experiments at Western University. These pressure cells have been specifically designed to test GFM as the emplacement dry density of GFM is less than for HCB. Figure 4-19(b) shows some results of culturing analysis which can be used to determine the abundance of aerobic, anaerobic and sulfate reducing bacteria found in the bentonite. Samples that were cultured from the inner and outer bentonite regions are shown in the top and bottom of Figure 419(b), respectively.[3] and exposed them to distilled water for 1, 3, 6, and 18 months. It can be seen that there is an initial growth period for aerobic and anaerobic (but not sulfate reducing) bacteria followed by a decline to background levels (background levels are quantified by analyzing the dry starting material bentonite shown on the left side of the figure) after about 6 months with little difference between the inner and outer samples. This indicates that even at a relatively low bentonite dry density microbial activity is inhibited in the long-term.

However, the initial scoping tests which occurred throughout 2020-2021 were conducted in an aerobic environment which is not representative of the long-term conditions of a DGR. Therefore, tests beginning in 2022 will repeat the work described above but in an anaerobic environment. The end goal of this project is to determine the minimum emplacement dry density at which bentonite, specifically GFM, will supress microbial activity in a DGR. Copper coupons will be embedded in the bentonite to help understand the synergistic effects of the proposed engineered barrier components.

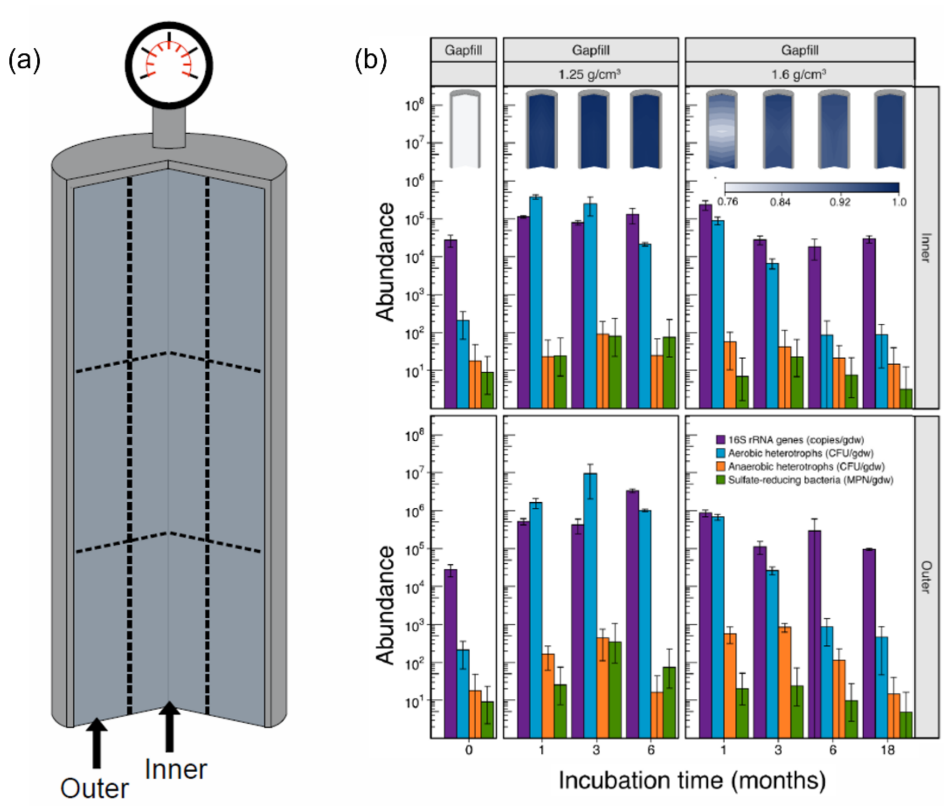


Figure 4-19: (a) Schematic of a Pressure Vessel for Ex-situ Microbiological and Corrosion Analyses Indicating the Locations of Sampling; (b) Abundances of Cultured Microorganisms from Pressure Cells Containing Bentonite with a Dry Density of 1.25 and 1.6 g/cm^3 versus Incubation Time. The Inner and Outer Sampling Results are on the Top and Bottom, Respectively.

4.2.3.1 Mont Terri HT (Hydrogen Transfer) Project

The Hydrogen Transfer experiment occurs at the Mont Terri underground rock laboratory in Switzerland. This is an in situ experimental study investigating the interactions and transport of hydrogen in a borehole in an Opalinus Clay environment. Hydrogen is injected near the borehole mouth and borehole water is analyzed to track the generation/consumption of the hydrogen. To date, it has been seen that hydrogen consumption does occur within the borehole and this has been attributed to microbiological activity. Work developed in 2021 and to be published in 2022 a numerical model to better understand the fate of hydrogen within the experiment (Damiani et al. 2022). The model supports the hypothesis that hydrogen in the borehole experiment is consumed by sulfate-reducing bacteria ultimately leading to a slight reduction in the water pH. However, this is counterbalanced by buffering species which naturally exist within the porewater. In the context of an NWMO DGR, the presence of bentonite is expected to supress any such behaviour of sulfate-reducing bacteria.

4.2.4 Field Deployments

While much work in the Engineered Barrier Science group has focused on laboratory-based experiments which focus on fundamental processes related to copper and bentonite integrity, more recent work is focused on the synergistic behaviour of copper embedded in bentonite deployed in DGR-like environments. This work is based off experience working with international collaborators in the Grimsel and Mont Terri Underground Research Laboratories (URLs) in Switzerland. However, the NWMO has adapted these experimental methodologies (so-called “module experiments”) and applied them in environments which more closely resemble potential Canadian DGR sites.

4.2.4.1 NWMO Borehole Deployments

Following on work conducted in 2020 which designed and fabricated a borehole testing system, 2021 saw the implementation of the testing system in an NWMO borehole in the crystalline rock of the WLON-Ignace area. The test system utilizes the module style experiment as described above but places it approximately 300 m deep inside an NWMO borehole. The module, shown in Figure 4-20a, containing copper coupons embedded in bentonite, is porous to allow the inflow of borehole water into the bentonite but contains a sintered steel mesh to keep bentonite from extruding out from the module. Six such modules were prepared and delivered to the borehole site where a crew successfully lowered the modules to around 300 m depth. This depth will be representative of a DGR environment in that it will be anoxic and contain water from the potential DGR site.

Figure 4-20b shows some crew members lowering equipment into the borehole. Prior to emplacement of the modules, water samples were taken for microbiological analysis to establish a baseline taxonomy to help with data interpretation later on. Filtering of borehole water for the microbiological analysis is show in Figure 4-20c.

Modules will remain in the borehole for up to a decade with removal of one or two modules occurring approximately every two years. Upon retrieval, modules will be sent to Western University for sampling and a full suite of corrosion and microbiological analysis will occur.

This is the first time that the proposed engineered barrier materials are being tested in one of NWMO’s potential DGR sites and the results are expected to contribute greatly to the understanding and confidence in the engineered barrier system.

Figure 4-20: (a) Loading of Module Inside an Anoxic Chamber. The Sintered Steel Mesh can be Seen Lining the Module Wall Along with a Copper Coupon Surrounded by Bentonite. (b) Crew Lowering Test Apparatus into the Borehole. (c) Filtering of Borehole Water Samples for Microbiological Analysis

4.2.4.2 Mont Terri IC-A (Iron Corrosion A)

In collaboration with the Swiss nuclear waste management organization, Nagra, NWMO are contributors to the IC-A (iron corrosion A) project at the Mont Terri underground research lab. This project is focused on studying the long-term synergistic behaviour of copper and steel embedded in bentonite and stored in a borehole in the native groundwater of the Mont Terri lab.

These experiments utilize the porous module apparatus similar to the experiments described in Section 4.2.4.1 and are also comparable to the ex-situ pressure cell experiments described in Section 4.2.3. Modules are retrieved every one to two years and are dissected to retrieve samples of bentonite for microbiological analysis and metallic coupons for corrosion rate measurements.

To date, modules which were placed in the borehole for 34 months have been retrieved and analyzed. Via mass-loss measurements recorded on electrodeposited and cold spray copper samples, average corrosion rates of 0.02 µm/yr to 0.17 µm/yr have been calculated which are well in line with the expected behaviour.

In 2021, a new set of modules were retrieved, and corrosion and microbiological analysis is underway. New modules were also placed into the borehole which contain copper coupons which were preoxidized and precondition by exposure to gaseous hydrogen sulfide. These samples are artificially aged and can simulate exposure conditions which may occur long into the future of a DGR. These new modules will remain in the borehole for several years before they are removed for analysis.

4.2.5 Corrosion Modelling

4.2.5.1 Localised Corrosion Modelling

4.2.5.1.1 Probabilistic Modelling

The development of a probabilistic model to predict the extent of localised (pitting) corrosion of copper canisters was on-going in 2021. The model accounts for not only the stochastic nature of pitting corrosion but also the variability and uncertainty in the repository environment and in how it evolves with time. Because of the availability of mechanistic information and of suitable input data, the model was developed on the assumption of aerobic, saturated conditions in the near field. This work was previously included a journal publication in 2020 (Briggs et al. 2020a) and in 2021 as report published by SKB (Briggs et al. 2020b).

4.2.5.1.2 Mechanistic Modelling

The development of a mechanistic model of pitting under an Evans droplet during the early aerobic phase of the DGR including the hysteresis effects of the drying and re-wetting of the copper coated container was initiated in 2020 with work on-going in 2021. During this early aerobic, unsaturated phase in the DGR it is expected that the corrosion mechanisms are similar to atmospheric corrosion, involving the deliquescence of surface contaminants, droplet formation, secondary spreading and spatial separation of anodic and cathodic processes due to the geometry of the droplet.

Work being conducted at the University of Florida is developing a finite-element model with the means to predict, mechanistically the rate and extend of localized damage due to copper corrosion. Presentation of model development and early results were given at the 240th Electrochemical Society Meeting in 2021 (Chen et al. 2021).

4.2.5.2 Full Scale Emplacement – Gas (FE-G) Oxygen Modelling

Gas monitoring in FE-G was on-going in 2021 and included gas composition studies, numerical modelling, and complementary table-top experiments. The gas composition in the FE-G, like a potential DGR, is controlled by different bio-, geo, chemical and transport processes. Continued in 2021 was analysis of aerobic conditions after backfilling, gas advection through the tunnel EDZ and plug, gas exchange with the clay host rock and other bio-chemical processes. Composition of the bentonite pore-space has been monitored since construction in 2014 to capture long term behaviour of, for example, unsaturated transport of corrosive species (e.g., O_2 and H_2S) and gas generation (e.g., H_2).

4.3 PLACEMENT ROOM SEALS AND OTHERS

4.3.1 Reactive Transport Modelling of Concrete-Bentonite Interactions

The multi-component reactive transport code MIN3P-THCm (Mayer et al. 2002; Mayer and MacQuarrie 2010) has been developed at the University of British Columbia for simulation of geochemical processes during groundwater transport. Prior reactive transport modelling work related to engineered barriers (e.g., bentonite) included the Äspö EBS TF-C benchmark work program (Xie et al. 2014), and the geochemical evolution at the interface between clay and concrete (Marty et al. 2015).

Reactive transport simulations with MIN3P-THCm have been continued in 2021 to investigate long-term geochemical interactions driven by diffusion-dominated transport across interfaces between bentonite, concrete and host rock (limestone and granite) in the near field of a repository. The impact of altered interfaces on the migration of radionuclides (i.e., I-129) has also been numerically investigated. Simulation results indicate that porosity reduction and pore clogging at the interfaces can significantly inhibit radionuclide migration (Xie et al. 2021). A journal paper documenting the reactive transport simulation across interfaces is expected in 2022.

MIN3P-TMCm is also being used to simulate the CI (Cement - OPA Clay Interaction) and CI-D (Diffusion Across 10-year Old Concrete-Claystone Interface) long-term experiment at the Mont Terri underground research laboratory to predict the cement-clay interactions. An anisotropic diffusion model has been implemented and verified against a 3D analytical solution. The model was then applied to simulate the in-situ diffusion experiment in three spatial dimensions taking into consideration complex geometry involving the vertical drill hole, the inclined test hole, the concrete clay interface, the surrounding anisotropic Opalinus Clay (OPA) and the thin 'skin' layer between the concrete and the OPA. Simulation results show that long-term tracer diffusion is enhanced parallel to the bedding due to the anisotropic properties of OPA in comparison to the case without considering anisotropy.

4.3.2 Gas-Permeable Seal Test (GAST)

Potential high gas pressure within the emplacement room due primarily to corrosion of metals and microbial degradation of organic materials is a significant safety concern for long term repository performance. To address this potential problem, Nagra initiated the GAST project at Grimsel Test Site, Switzerland in late 2010. The main objective of GAST is to demonstrate the feasibility of the Engineered Gas Transport System which enables a preferable flow path for gas at over-pressures below 20 bars where the transport capacity for water remains very limited. NWMO has been part of the GAST project since its inception.

GAST field experiment was delayed due to a major leak event occurring in 2014 followed by a very slow saturation process in the sand bentonite mixture. In the end of 2021, the long-lasting saturation process completed and preparation work for a full-scale gas flow test was underway immediately.

In 2019, a smaller scale, well instrumented laboratory experiment - mini-GAST was initiated at UPC (Polytechnic University of Catalonia), Barcelona, Spain. The mini-GAST project aims to mimic the GAST experiment in a much better controlled fashion in the lab within a much shorter testing time frame. The mini-GAST experiment comprises of two semi-cylindrical shape mock-up tests, MU-A (50 cm in length and 30 cm in diameter) and MU-B (1/3 size of MU-A).

In 2021, the 2nd MU-B test (gas injection) was conducted after its initial tryout experiment in 2020. On top of the experiences learnt from MU-B tests, MU-A was assembled to carry out its very first test in 2021. Before the lab experiment, Code Bright was used to perform 3D one-phase (liquid) and two-phase (liquid and gas) flow modelling to imitate the MU-A test conditions.

4.3.3 DECOVALEX Modelling

4.3.3.1 DECOVALEX 2023 Task C: Coupled THM Modelling of the FE Experiment

DECOVALEX is a multidisciplinary, cooperative international research effort in modelling coupled Thermal-Hydraulic-Mechanical-Chemical (THMC) processes in geological systems and addressing their role in Performance Assessment for radioactive waste storage (Birkholzer et al., 2019). One of the projects in DECOVALEX-2023 is coupled thermal-hydraulic-mechanical modelling of the FE Experiment – Task C.

Task C of DECOVALEX-2023 ties into the FE experiment, with the aim of building models capable of representing the FE experiment and in particular pore pressure build-up in the Opalinus Clay associated with heating (Nagra, 2019). Similar work has been done before in other host rocks through DECOVALEX-2019 (Seyedi et al, 2021). The challenge here is in representing a large experiment in numerical codes and using the simulations to help analyse a large dataset from the experiment. Task C involves comparison of the models and methods used in coupled THM modelling of engineered materials. These models will also be used to investigate how engineering factors (e.g., shotcrete, tunnel shape) affect pore pressure safety margins in the repository.

NWMO participates in Task C modelling activity as one of the ten international modelling teams to validate the NWMO developed COMSOL THM model in application in the coupled THM modelling of the engineered materials used in the nuclear waste management programs.

The task is divided into three steps:

Step 0: Preparation phase: Benchmarking of the models against some simple, tightly defined test cases. It includes a 2D T simulation, a 2D TH+vapour simulation, and a 2D THM simulation.

Step 1: FE heating phase: Modelling the change in pore pressure in the Opalinus Clay as a result of heating in the FE experiment. This requires 3D THM simulations with representation of partially saturated conditions. It includes three sub-steps: predication, analysis and calibration.

Step 2: FE ventilation phase: Modelling of absolute pressures in the Opalinus Clay, which will require representation of the ventilation of the FE tunnel prior to heating. Modelling teams can choose the complexity of the representation of excavation and EDZ development.

Step 3: Options for later parts of the task include:

- Consideration of more realistic geometry / additional materials etc
- Analysis of experiments on temperature dependent geomechanical properties
- Sensitivity analyses (e.g., considering the impact of higher temperatures)
- Anything else that comes from the comparison of models and data during Steps 1 and 2.

In the period of 2020-2021, Step 0 was finished. Ten modelling teams have performed the 2D thermal, coupled TH and coupled THM modelling FE experiment using different numerical modelling programs and the results are compered between different teams. The document for these comparisons between different teams is under preparation as an interim DECOVALEX report.

In 2021, Step 1 – prediction modelling of the FE experiment is on-going. In this step, all of the thermal, hydraulic and mechanical parameters and model geometry for the FE experiment are well defined and supplied to different modelling teams. The focus of 2022 work will be comparing results between different modelling teams and between numerical models and experiment measurements.

4.3.3.2 DECOVALEX 2023 Task F: Performance Assessment

The DECOVALEX program is interested in coupled processes (e.g., thermal, hydrological, mechanical, and chemical) relevant to deep geologic disposal of nuclear waste. Task F of DECOVALEX-2023 involves comparison of the models and methods used in post-closure performance assessment of deep geologic repositories.

Task F considers the generic reference case describing a repository for commercial spent nuclear fuel in a fractured crystalline host rock is proposed as the primary system for comparison. The NWMO is participating in the crystalline comparison. A second generic reference case describing a repository for commercial spent nuclear fuel in a salt formation (bedded or domal) is also a component of Task F however the NWMO is not participating in that component of task F.

The primary objectives of Task F are to build confidence in the models, methods, and software used for performance assessment of deep geologic repositories, and/or to bring to the fore additional research and development needed to improve performance assessment methodologies. The objectives will be accomplished through a staged comparison of the models and methods used by participating teams in their performance assessment frameworks, including: (1) coupled-process submodels (e.g., waste package corrosion, spent fuel dissolution, radionuclide transport) comprising the full performance assessment model; (2) deterministic simulation(s) of the entire performance assessment model for defined reference scenario(s); (3) probabilistic simulations of the entire performance assessment model; and (4) uncertainty quantification and sensitivity analysis methods/results for probabilistic simulations of defined reference scenario(s).

In 2021, Task F participants completed benchmarking of the various software programs and performance assessment tools used in Task F against hydrogeological flow and transport problem with known analytical solutions. The NWMO will be performing these benchmarks and will complete the Task F work with the Integrated System Model (See Section 6.4.3.1.1) and its constituent codes COMSOL and HydroGeoSphere. Benchmark Comparisons are expected to be published in early 2022.

In 2021, Task F participants contributed to the definition of the generic crystalline rock assessment case. At present the generic crystalline rock site will be a rectangular domain with a topographic high as one end of the site. The site rock and fracture characteristics will be based on the Posiva characterization of Onkalo site. The hypothetical repository will be based on the KBS-3 vertical in-floor disposal concept. The focus of the 2022 work will be developing and comparing results of the generic crystalline site assessment approaches and results across the various participants.

4.3.4 Shaft Seal Properties

In 2021, the NWMO continued with its program to identify an optimized shaft seal mixture by evaluating the behavior of bentonite/sand blends having composition ratios other than 70:30. In this study, the use of a crushed limestone sand is being examined in addition to granitic sand. Composition ratios of bentonite/sand of 50:50, 60:40, 70:30, 80:20 and 90:10 (by weight) are being assessed by using two different salinity fluids, CR-10 (TDS 11 g/L) and SR-Sh (TDS 325 g/L), approximating groundwater conditions for crystalline and sedimentary sites, respectively. The tests evaluate the following:

- Compaction/fabrication properties of the materials (to Modified and Standard Proctor density)
- Consistency limits (Atterberg Limits) and free swell tests
- Moisture content and density of fabricated material
- Mineralogical/chemical composition, including measurements of montmorillonite content
- 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 fabricated and fully saturated condition
- Mineralogical/chemical composition of the materials exposed to brine for an extended period of time

Based on the results to date, it is anticipated that for low salinity groundwater conditions (CR-10), compaction to 98% of the Standard Compaction Maximum Dry Density of the bentonite/sand mixtures studied will be sufficient to achieve the swelling pressure and hydraulic conductivity targets (>100 kPa and <10^{-10} m/s, respectively). Under high salinity conditions (SR-Sh), it is expected that heavy compaction to approximately 95% of Modified Compaction Maximum Dry Density will be required to achieve swelling pressure and hydraulic conductivity targets for the blends studied. The swelling pressures observed for the materials examined in this study generally were also within the range of previously observed values for both low and high salinity conditions.

Some effect of aggregate composition on swelling pressure was observed. The bentonite-crushed limestone mixtures showed discernibly lower swelling pressure than the mixtures with granitic sand. A larger database should be developed to confirm this phenomenon as it was not evident in the hydraulic conductivities measured for these same specimens

4.3.5 Low Heat High Performance Concrete

Concretes can potentially be used in the shaft seal, room plugs, and flooring in deep geological repositories (DGRs). Particularly, low alkalinity concretes are favored for use in DGRs, as they will minimize the potential for chemical interaction with bentonite-based sealing materials in the repositories. The NWMO reference concrete is Low Heat High Performance Concrete (LHHPC). Since measurements of the material properties of this reference LHHPC were needed in support of the proposed DGR concept, the NWMO launched a work program in 2019 to fabricate samples of the optimize LHHPC and measure its properties. The LHHPC mix was optimized based on the original reference concrete mix design, using mix ingredients from local and sustainable sources.

The work program was completed in 2021 and evaluated the following LHHPC properties:

- density
- porosity
- unconfined compressive strength
- hydraulic and heat conductivity
- shrinkage rate
- maximum temperature rise
- slump flow

- pH
- free silicon content in silica fume

Figure 4-21 shows a permeability testing cell and a hollow LHHPC specimen for the hydraulic conductivity testing. Different types of water (e.g., CR-10 crystalline rock groundwater or SR-270 sedimentary rock groundwater) were used for the curing and testing of various material properties. The results indicate that the optimized LHHPC met the relevant performance requirements.

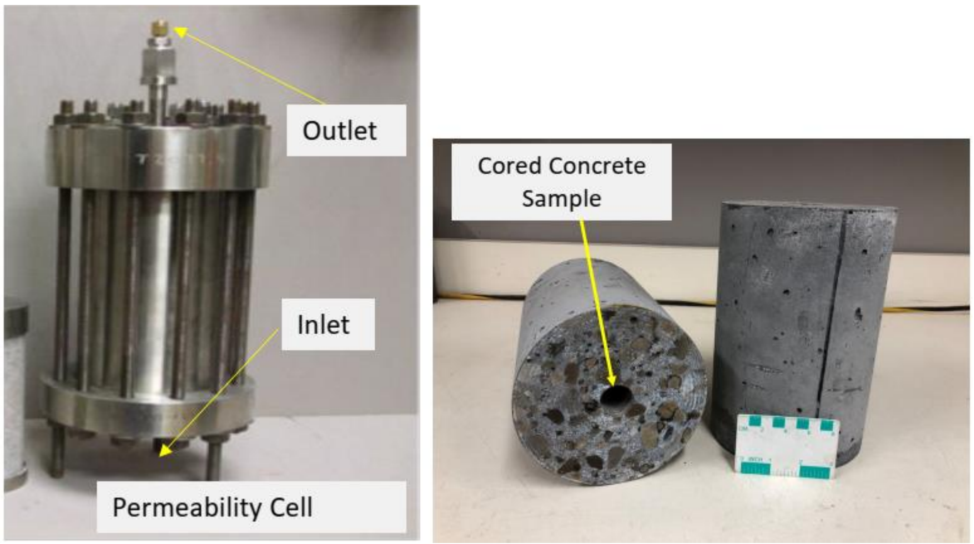
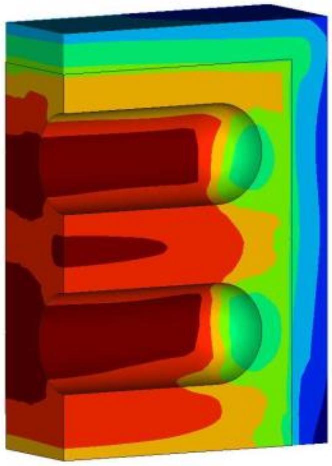


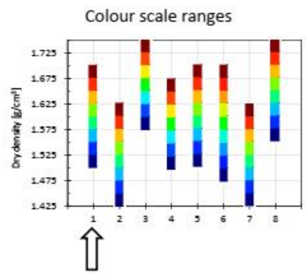
Figure 4-21: A Photograph of the Permeability Cell (left) and Hollow LHHPC Specimen (right)

4.3.6 Thermo-Hydro-Mechanical Modelling of a NWMO Placement Room

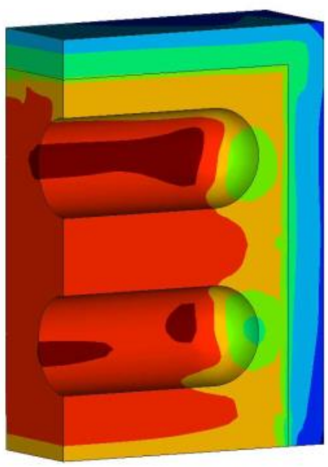
In 2021, the NWMO continued to use fully coupled Thermo-Hydro-Mechanical (THM) CODE_BRIGHT models to study the unique NWMO placement concept. A sensitivity analysis of the previous numerical models using various initial dry densities of HCB and GFM without air gaps was conducted to analyze the evolution of emplacement densities at saturation. The model results showed similar dry density distributions at full saturation, higher dry density near the UFC and lower near and inside the GFM. Figure 4-22 shows two examples of the numerical results of final dry densities of HCB, GFM, with Model 1 demonstrating the minimum allowable dry densities of 1.7 / 1.41 g/cm^3 for HCB and GFM, while Model 2 illustrates a calculation for dry densities below these minimum specifications. Within the figure, data from additional case studies is also presented, illustrating low- and high-density cases for both HCB and GFM. As expected, higher initial dry densities of HCB, produce higher final average dry densities of the entire buffer system; however, it is worth noting that the density is not uniform following wetting.



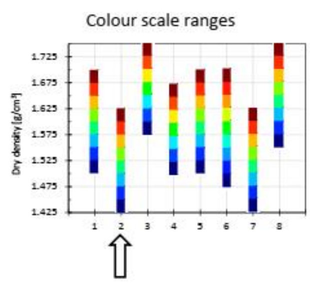
	ρ_d [g/cm³]
Max	1.69
Min	1.51
Volume average Block	1.65
Volume average GFM	1.56
Volume average Total	1.63



(a) Model 1 with HCB (1.7 g/cm³) and GFM (1.41 g/cm³)



	ρ_d [g/cm³]
Max	1.61
Min	1.44
Volume average Block	1.57
Volume average GFM	1.49
Volume average Total	1.55



(b) Model 2 with HCB (1.6 g/cm³) and GFM (1.41 g/cm³)

Figure 4-22: Computed Final Dry Densities of HCB, GFM and the Entire Buffer

The numerical models with air gaps were conducted to examine the effect of air gaps on final dry densities of HCB and GFM at saturation. All models with air gaps showed a decrease in dry density. It was directly linked to the change in volume of the buffer due to the presence of the air gaps. The numerical results indicated that the air gaps induced the decrease in overall dry density by up to 5% and in swelling pressure by up to 30% in the entire buffer region.

4.3.7 Coupled Thermo-Hydro-Mechanical Benchtop Experiments

In late 2018, the NWMO and its contractor (the National Research Council of Canada) launched a work program to design and construct test cells to perform experiments examining the Thermal-Hydro-Mechanical (THM) response of HCB and GFM for use as a component in the Engineered Barrier System of the multibarrier concept. Results of the experiments will provide useful information for advancing the design of seals and will be compared against numerical THM models such as COMSOL and CODE_BRIGHT.

Two cylindrical experimental cell designs have been developed, one to measure the THM response of HCB and GFM when exposed to a temperature boundary condition (called T apparatus) and the other to measure the THM response when exposed to both temperature and hydraulic boundary conditions (called THM apparatus). The T apparatus is approximately 80 cm in length and 34 cm in diameter and has a resistive heater along the central axis of the cylindrical cell. The heater is then surrounded by concentric rings of highly compacted bentonite and gapfill as shown in Figure 4-23. Construction of the heating only cells was completed in 2020. After a first trial of the T apparatus in June 2021, modification of the instrumentation plan and the heater design was needed. Sensors of moisture content and relative humidity are calibrated with different densities of HCB and GFM, and the heater design is being modified.

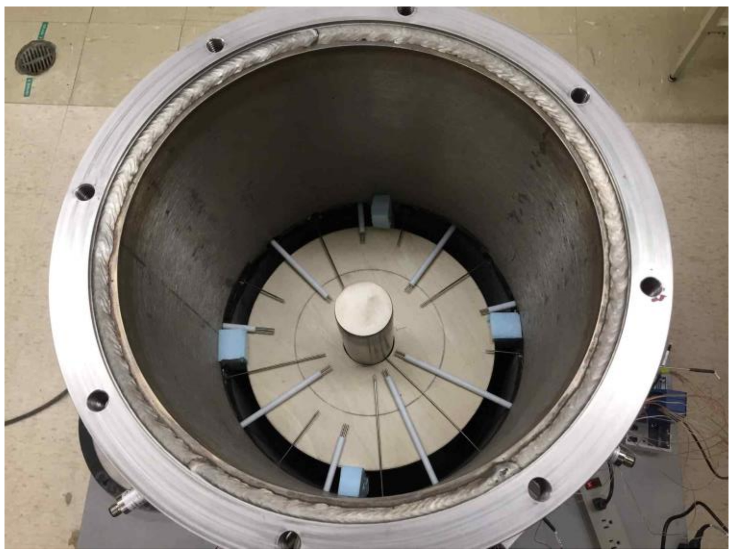


Figure 4-23: Heating Only Apparatus

The second cell (THM apparatus) is similar to the T apparatus (see Figure 4-24). It is cylindrical, contains a resistive heater along the centre axis and contains concentric rings of highly compacted bentonite and gapfill. However, the THM apparatus includes both heating and wetting of the bentonite. Water can be delivered by a pressurized water delivery system. The dimension of the THM apparatus is also smaller (48 cm in length and 30 cm in diameter) to help achieve faster saturation of the HCB and GFM. Due to the reduced cell size, the THM apparatus only contains a single instrumented sensing zone with temperature, relative humidity, and moisture sensors. Swelling pressure of the HCB and GFM during hydration will be also measured using strain gauges on the perimeter of the cell. The design and construction of the THM apparatus were complete in 2021, and its water delivery system is being developed and tested.

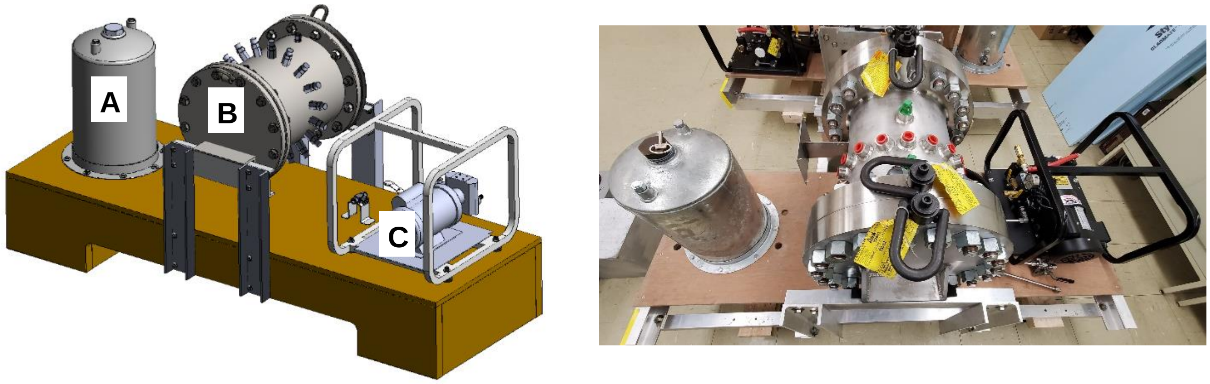


Figure 4-24: Rendering of the THM apparatus Design (A) Is the Water Reservoir, (B) Is the Test Cell, and (C) Is the Water Pump

5 GEOSCIENCE

5.1 GEOSPHERE PROPERTIES

5.1.1 Geological Setting and Structure – Lithostratigraphic Framework for the Paleozoic Bedrock of Southern Ontario

The Paleozoic bedrock of southern Ontario contains large volumes of groundwater. The groundwater is fresh at shallow depths and is an important source of potable water. At greater depths groundwater is increasingly saline yet still has a variety of practical uses such as disposal of saline oilfield water and are locally being considered for CO_2 sequestration. Locally, at intermediate depths groundwater aquifers in southern Ontario contain dissolved hydrogen sulfide (H_2S) generated by a diverse but poorly understood microbial ecosystem dominated by sulfur proteobacteria. This “sulfur water” is a known corrosion hazard for unprotected steel and concrete in subsurface infrastructure such as tunnels, mine shafts, petroleum wells and foundations.

In 2021 the Geological Survey of Canada led the development of a hydrostratigraphic model for southern Ontario (Figure 5-1). The model was based on re-assigning lithostratigraphic model layers from a recently developed 3-D geologic model (Carter et al. 2021a,b) into 14 hydrostratigraphic layers based principally on hydrogeologic characteristics in the intermediate to deep groundwater regimes. Hydrostratigraphic units assigned as aquifers are sub-divided into three distinct hydrochemical regimes: brines (deep), brackish-saline sulfur water (intermediate), and fresh (shallow). The hydrostratigraphic unit assignment provides a nomenclature and definition for regional flow modelling of potable water and deeper fluids. The model includes 3-D representations of oil and natural gas reservoirs which form an integral part of the intermediate to deep groundwater regimes, 3-D static level surfaces for deep Cambrian brines and the fresh to sulfurous groundwater of the Lucas-Dundee regional aquifer, inferred shallow karst, base of fresh water, Lockport Group TDS, and the 3D lithostratigraphy. Similar to the lithostratigraphic model, the hydrostratigraphic model is constructed using Leapfrog Works at 400 m grid scale.

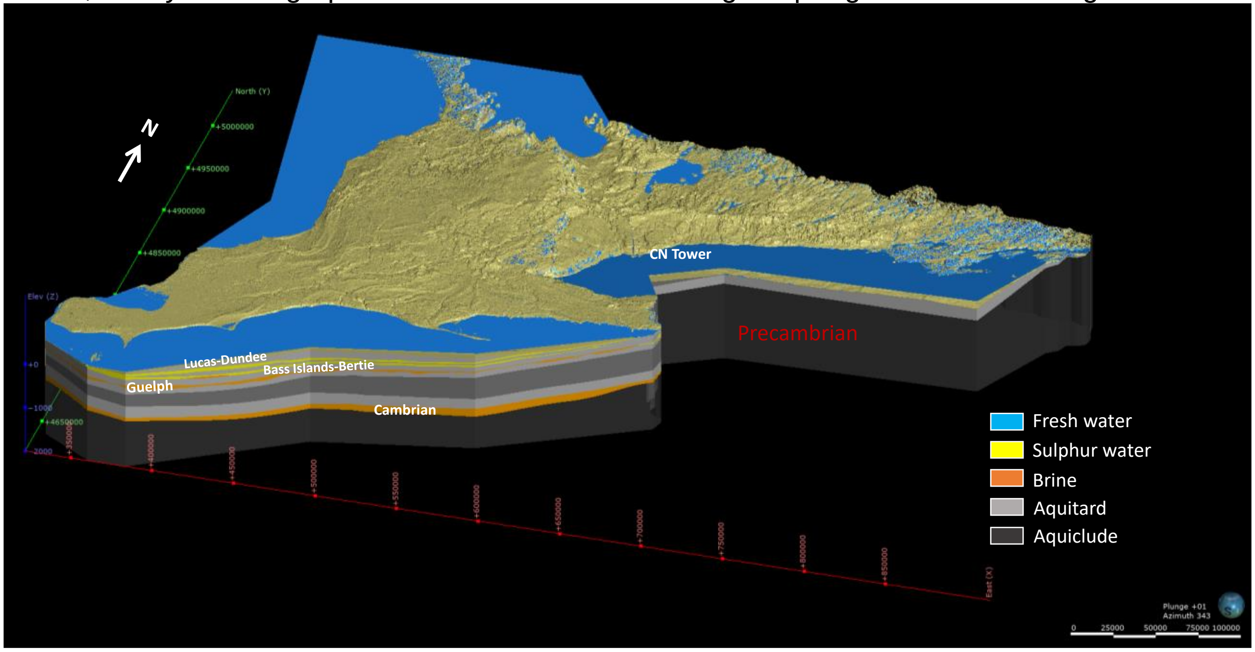


Figure 5-1: 3D Hydrostratigraphic model for southern Ontario (Carter et al., 2021b)

5.1.1.1 Fractures and Fracture Zones, Faults, and Joints Numerical Methods – Discrete Fracture Networks

Fracture network modelling involves using 3-dimensional (3-D) geostatistical tools for creating realistic, structurally possible models of fracture zone networks within a geosphere that are based on field data. The ability to represent and manage the uncertainty in the geometry of fracture networks in numerical flow and transport models is a necessary element in the development of credible geosphere models. Fracture network modelling will also be used in 3-D integrated geosphere models. The creation of fracture network models in MoFrac (software that generates 3-D fracture network models for rock mass characterization) is a multistep process that involves integrating interpretations of lineament data and other available field data to define fracture orientations and size distributions.

MoFrac is capable of creating DFN models at the tunnel-, site- and regional scale (e.g., Bastola et al. 2015; Junkin et al. 2017, 2018, 2019a, 2019b, 2020). During 2021, further development and refinement of version 4 of Mofrac was conducted through the research program. The focus of the development activities was on the generation of stochastic and semi-deterministic fracture generation, as well as enhancing computational performance.

5.1.1.1.1 Mont Terri Seismic Imaging (SI-A) experiment

During 2020, the NWMO joined as a partner in the SI-A Experiment (Seismic Imaging Ahead of and Around Underground Infrastructure) to investigate the applicability of high-frequency seismic impact or vibration sources, combined with three-component geophones integrated in rock bolts, for transmission and reflection imaging in an argillaceous environment to allow imaging of faults and fractures. The experiment is a high-resolution exploration test with resolution in the dm- to m-scale and within an observation range of several decameters to a few hundreds of meters. In 2020, seismic measurements were completed in Ga08, Ga04 and Niche CO2. In 2021, the focus was on acquisition of a seismic profile along the safety gallery, crossing both the upper and lower boundaries of the Opalinus Clay. Measurement was performed along a 400 m-long section within the safety gallery, using a 120 m-long land streamer with 120 geophones and a vibration source with a sweep of 30-120Hz. In future phases, the experiment focus will be on data processing/imaging and potentially additional data acquisition.

5.1.1.2 Metamorphic, Hydrothermal, and Diagenetic Alteration

5.1.1.2.1 Hydrothermal Alteration in Crystalline Rocks

An understanding of the brittle and ductile deformation seen within the granitoid plutons of the Wabigoon Subprovince is essential to understanding previous and potential future fluid migration pathways. The hydrothermal/metasomatic alteration is directly linked to the presence of brittle fractures, as they act as paths for fluid to migrate. Research conducted at Lakehead University characterizes the relationship between the brittle deformation, ductile deformation, and the hydrothermal/metasomatic alteration of twelve granitoid plutons across the Wabigoon subprovince in order to provide insight into the tectonic evolution of the plutons and their corresponding fluid migration pathways.

This research is unique in that it uses granitoid rocks of the Wabigoon Subprovince, instead of the host greenstone belts, as proxies of metamorphism in the region. This research combines structural studies with an examination of the mineralogy and petrology of the hydrothermal alteration assemblages. In addition to structural studies, the study includes petrographic analysis and mineral chemistry characterization. Figure 5-2 shows the localities for sample collection and structural mapping as part of the research.

Results of the structural and petrographic analysis on the twelve granitoid plutons are as follows:

- Each pluton has (on average) steeply dipping chlorite and/or epidote infilled shear fractures that record sub-horizontal displacement along shear surfaces, consistent with an Archean transpressive tectonic history (dominant component of strike-slip deformation with a lesser reverse movement component).
- Variations in the strikes of the brittle shear fractures are seen across most plutons, which could be the result of non-coaxial strain in which the rigid and competent granitoid plutons themselves have undergone a component of rigid body rotation, resulting in the rotation of the maximum elongation direction. Since Archean transpression is largely believed to have been dextral, the plutons would have rotated clockwise. The degree of rotation a pluton has experienced is likely to be a function of the shape and size of the pluton. For example, the elongated Revell Batholith would be harder to rotate than a smaller, more rounded pluton such as the Ottertail pluton. Theoretically, plutons such as the Revell Batholith likely record more consistency in the orientation of the brittle fractures.
- The alteration of the wall-rock adjacent to the brittle fractures consists of the replacement of feldspars by epidote and white mica. Other alteration minerals include chlorite, sphene, calcite and hematite.
- Peak deformation textures (as noted by the presence of ductile dislocation creep textures within feldspars) greater than 450°C, corresponding to the onset of amphibolite facies metamorphism for all twelve plutons.
- Evidence for ongoing brittle deformation during peak metamorphic conditions in six of the twelve plutons, with brittle deformation and associated alteration continuing post peak metamorphism and into exhumation.

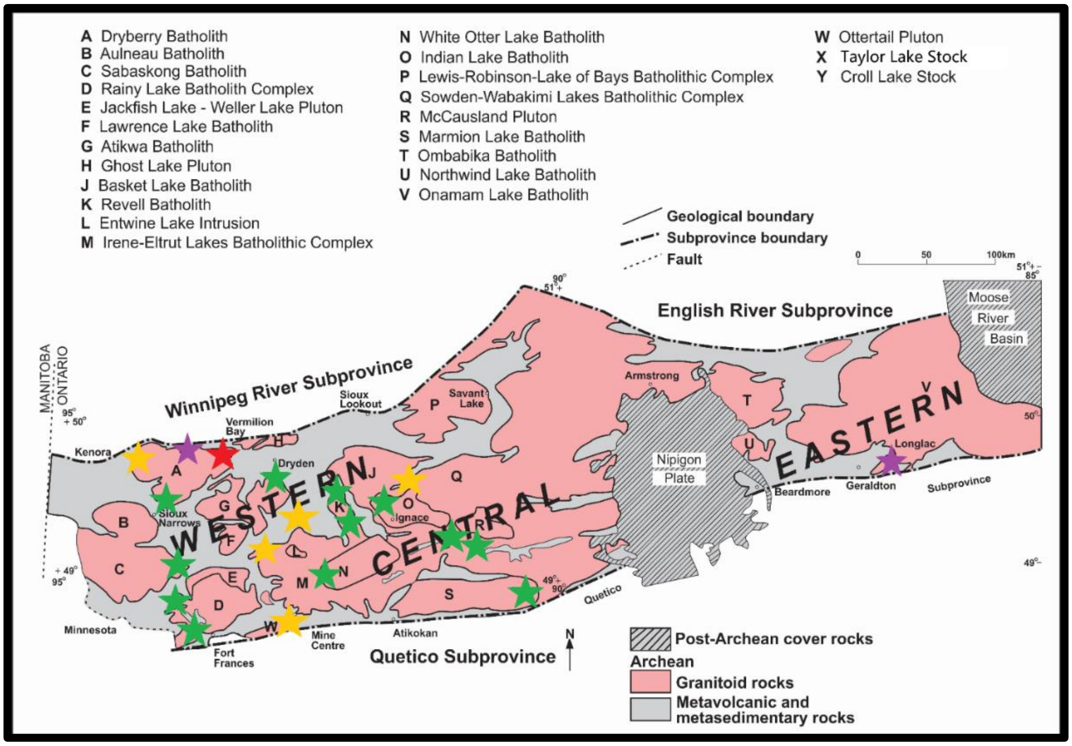


Figure 5-2: Outcrop Locations where the Hydrothermal Alteration and Deformation of the Plutons Have Been Studied. Green Stars Represent 1 Outcrop, Red Stars Represent 2 Outcrops, Yellow Stars Represent 3 Outcrops and Purple Stars Represent 5 Outcrops

The research also assessed the mineral chemistry of the fracture infill and wall rock alteration minerals via SEM-EDX analysis. Six chlorite veins were chosen for stable isotopic analysis (δD and $\delta^{18}O$) to calculate the isotopic signature of the hydrothermal fluid from which the chlorite was derived, which can be used to place constraints on the source of the hydrothermal fluid. Cathodoluminescence imaging was also completed on the quartz and feldspars to provide insight into the effectiveness of this tool when studying alteration. Results of this work are as follows:

- White mica (predominately phengite) and epidote mineral analysis show great consistency across the Wabigoon Subprovince, regardless of occurrence type. Chlorite shows scatter likely related to the composition of the host rock from which the fluid was derived and/or temperature conditions.
- The δD_{fluid} and $\delta^{18}O_{fluid}$ values of the hydrothermal fluid calculated from measured δD and $\delta^{18}O$ values of chlorite infilled shear fractures range from -30 to -45‰ and 5.6 to 7.1‰, respectively, recording a metamorphic water signature that likely stems from the devolatilization of the surrounding host greenstone during regional Archean metamorphism (Figure 5-3).
- Cathodoluminescence imaging is an effective method in analyzing the alteration and associated fluid flow migration through feldspars that can not be seen with standard petrographic analysis (Figure 5-4). Color hue variations in the imaged feldspars clearly show the incorporation of trace elements and/or REE’s associated with fluid flow. The

imaging shows the greatest color hue variations in the highest strain samples, consistent with the notion of brittle deformation being essential to hydrothermal fluid flow.

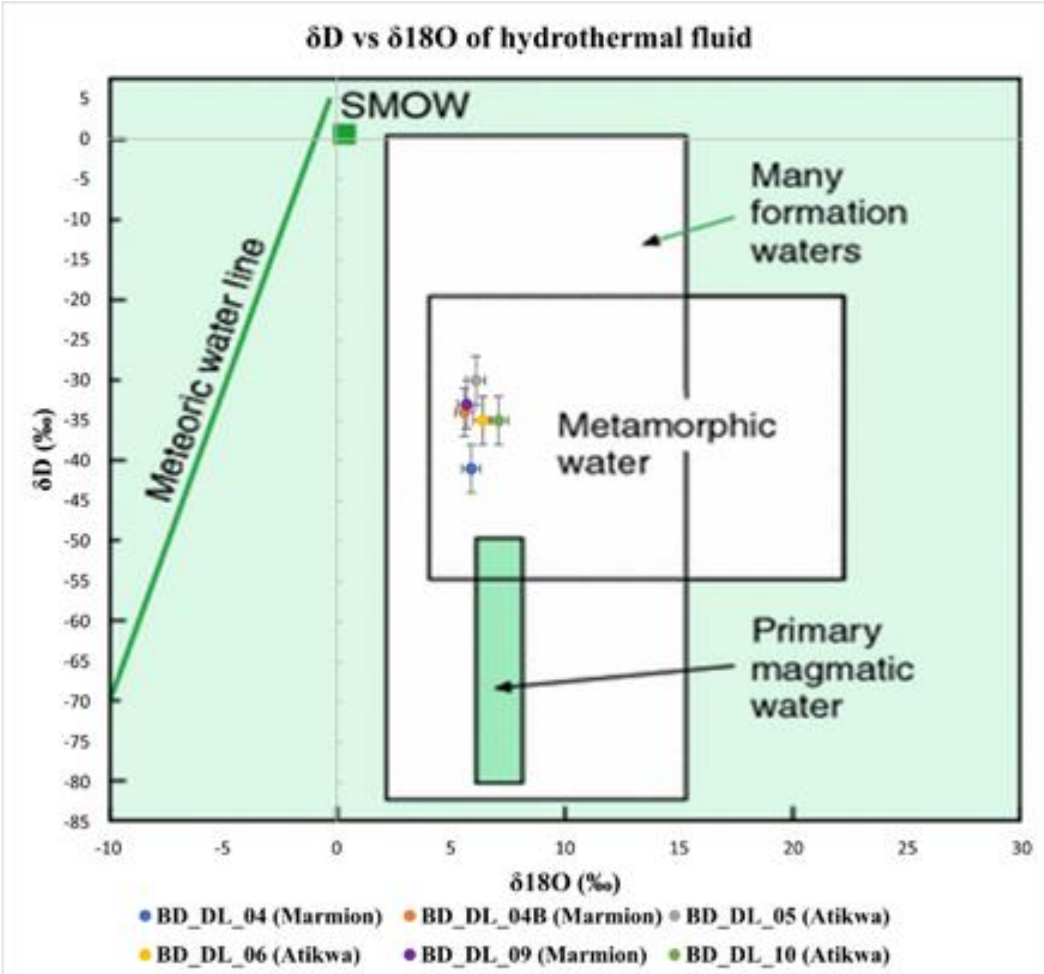


Figure 5-3: Calculated Stable Isotope Signatures of the Hydrothermal Fluid from Six Chlorite Infilled Shear Fractures. All Points Plot Within the Metamorphic Water Domain

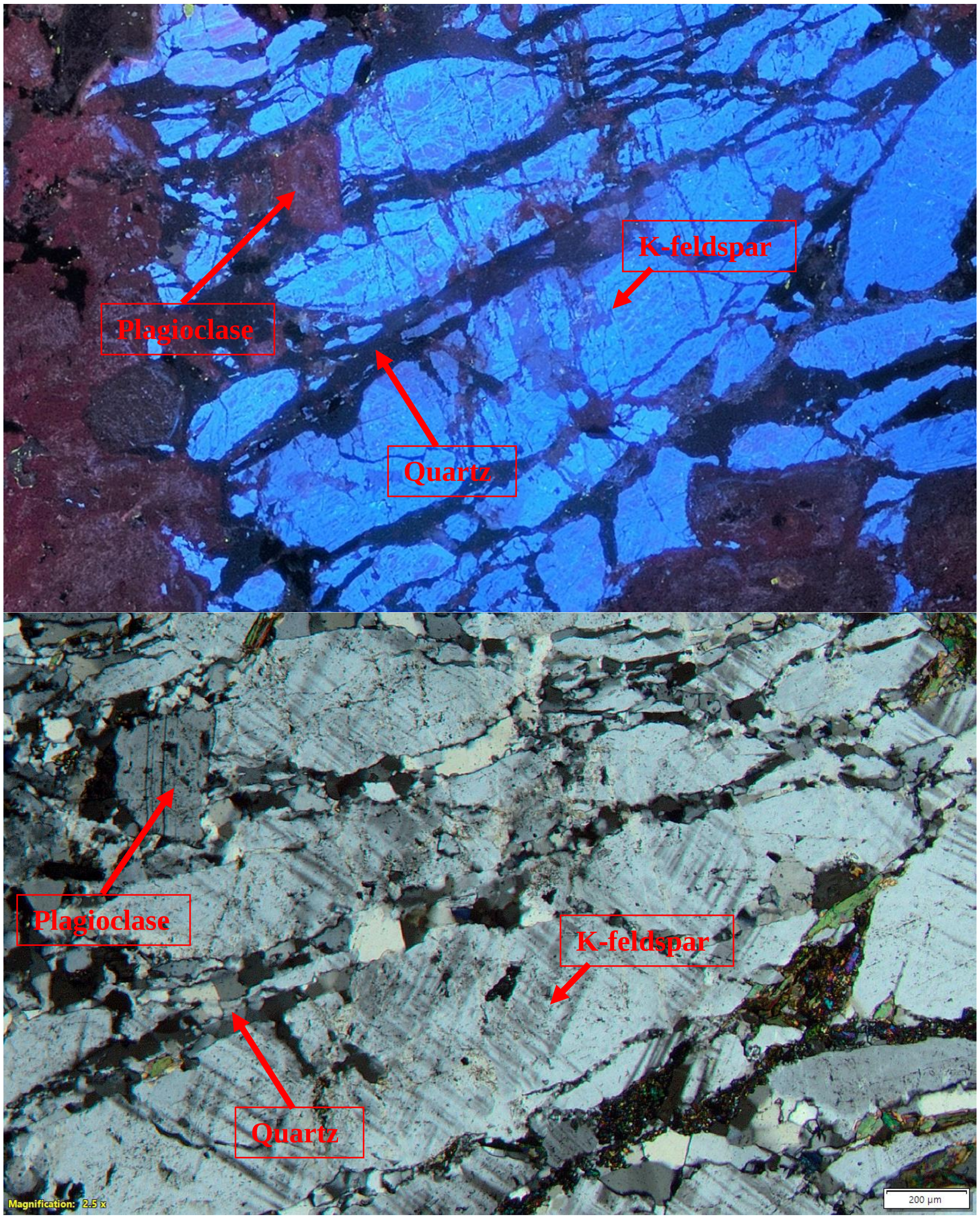


Figure 5-4: A Comparison of the Cathodoluminescence Image (top) and its Corresponding Cross Polarized Transmitted Light Image (Bottom - Slightly more Zoomed in). Variations in the Blue Hue of the K-feldspars Seen in the CL Image Correspond to an Uptake of REE's and/or Trace Elements Associated with Hydrothermal Fluid Flow that Cannot be Seen in the Bottom Cross Polarized Transmitted Light Image

5.1.1.2.2 Diagenetic Alteration of Sedimentary Formations

5.1.1.2.2.1 Dolomitization in Southern Ontario

Research has been underway since 2015 to investigate the nature and origin of strata-bound, near-horizontally layered dolomitized beds occurring within the bedrock formations of the Black River Group in the Huron Domain of southern Ontario. A summary of the research conducted between 2015 and 2017 is available in Al-Aasm and Crowe (2018).

During 2019, the research scope shifted to focus on the determination of Rare Earth Elements (REE) in both previously examined samples and new samples collected during 2018. The purpose of this next phase of the research is to better understand the provenance of the source fluids involved in dolomitization the formations. This research further improves the fundamental understanding of fluid sources, movement, and interactions with the sedimentary rocks over geologic time. Over the past two years, more recent research findings were published (Tortola et al. 2020; Al-Aasm et al. 2021). Due to laboratory closures associated with the pandemic, the completion of some laboratory analyses for this research were delayed. Consequently, a draft of the final publication summarizing all work conducted since 2014 is now expected in 2022.

5.1.1.2.3 Clumped Isotope Paleothermometer for Dolomite

A research project was initiated in 2021 with the GSC and NRCan that aims to use a new approach to assess fluid longevity within carbonate sedimentary rock mass. The clumped-isotope thermometer is a relatively new geothermometer which functions on the principle that rare 'heavy' isotopologues in a molecule prefer to bond together, with a dependence on the temperature of the system. Specifically, ^{13}C and ^{18}O in a carbonate mineral are thermodynamically ordered or 'clumped' depending on the temperature of the depositional environment. Determining the abundance of clumped isotopes in carbonate ($\Delta 47$) then allows constraints to be placed on the formation temperatures.

This approach has the advantage of being able to directly infer the isotopic composition of the parent fluid, which is often difficult to reconstruct given 1) the prevalence of diagenesis in buried sedimentary successions and 2) the formation of secondary minerals over a wide range of temperatures. Using clumped isotopes analysis of carbonates as a tool, and with the objective of establishing a new paleothermometer for dolomite as well, key aims of the research program will be to reappraise the evolution of the Ordovician limestone sedimentary units in Southern Ontario and provide additional insights on the origin of mineralising fluids and post-depositional modifications to the rock.

During 2021, the first step of work included hiring of an experienced staff member to help lead this project. This was completed by mid-2021. Several key tasks were initiated to ensure that: 1) the GSC instrumentation was optimized, 2) the required dolomite temperature calibration anchors were produced, 3) a data standardization scheme for dolomite was established. Work will continue on these tasks and several other calibration-related tasks for both dolomite and calcite in 2022.

5.1.2 Hydrogeological Properties

5.1.2.1 Hydraulic Properties of Fractured Crystalline Rock

5.1.2.1.1 Advances in Defining Hydraulic Properties of Crystalline Rock

Research at the University of Waterloo is being undertaken to develop improved approaches to characterize the hydraulic behaviour and evolution of groundwater systems in Canadian Shield settings. Snowdon et al. (2021) provided an extensive compilation of hydraulic properties in crystalline rocks of the Canadian Shield. Data were drawn from technical documents developed by Atomic Energy of Canada Ltd between 1975 and 1996 and includes 620 permeability estimates from sites across the Canadian Shield. During 2021, the database was verified and used to define depth dependent variations in EPM rock mass and fracture zone permeability for Canadian Shield settings. The depth dependent variations determined specifically for plutonic rocks within the Canadian Shield will be used as a platform to develop early site-specific groundwater models for the WLON-Ignace area, which will be refined with site-specific data as it becomes available.

5.1.2.1.2 HM Coupling of Rock Mass Stress and Permeability

In 2020, new research was initiated to evaluate the impact of the stress on the equivalent hydraulic conductivity of fractured rock masses and how this impact is also dependent on the fracture system in-situ properties (geometrical and hydraulic properties). To address these issues, intensive numerical simulations with the software DFN.lab are conducted, and an analytical framework is developed. In this case, a constitutive law to relate equivalent hydraulic conductivity to in-situ stresses with a parametrization based on the Discrete Fracture Network (DFN) properties is required. The “permecability” concept is a simplified hydromechanical coupling at the scale of the fractures with a transmissivity-stress relationship.

During 2021, sensitivity analyses initiated in 2020 were advanced to include cases ranging from examining sensitivity to the parameters of the transmissivity-stress law (range of variation between residual and maximum hydraulic aperture), to simplified stress variation scenarios such as depth dependency or glaciation cycles and to the generation seed for DFN realization generation. Building of an analytical framework was also further investigated, and can be summarized as:

$$K(\theta) \sim p^{*}(\theta) \cdot \langle T_{(\theta)} \rangle_g$$

In this equation, $K(\theta)$ is the rock mass equivalent permeability in any direction (θ), $p^{*}(\theta)$ is the effective connectivity of the DFN structure in the direction θ, and $\langle T_{(\theta)} \rangle_g$ is an averaging term over the transmissivity distribution, also dependant on the direction g. The numerical set-up of DFN.lab was also used to evaluate the analytical framework for configurations of increasing complexity (from single or fracture pairs configurations to the realistic DFN models used as reference model in the sensitivity analyses). During 2021, first drafts of a technical note and a journal article were prepared, and a conference presentation was given (Davy et al., 2021).

5.1.2.1.3 Äspö Task Force – Task 10

SKB originally initiated the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes (the Task Force) in 1992 to enhance the understanding and increase the ability to model problems of interest in the field of groundwater flow and solute transport. In 2020, NWMO re-joined the Äspö Task Force to participate in Task 10 which is dedicated to building confidence in and "validating" models of flow and transport in fractured rock. The objective of this task is to develop pragmatic approaches to model validation. The first step was the development of a "White Paper" to set out possible approaches for discussion and further refinement by the members. Task 10.2 which focusses on the single fracture scale and channelling will be undertaken first. Subsequent tasks will consider networks of fractures at larger scales.

Flow channelling in fractured rock is a phenomenon that occurs on different scales and can have a range of safety related implications. For example, channelling is relevant to:

- Characterization and interpretation of groundwater flow and transport in a fractured host rock,
- Assessing the potential for migration of meteoric water from the near surface to repository depths and subsequently radionuclide transport from the repository in the unlikely event of breached canisters,
- Inflows of groundwaters into deposition holes or emplacement rooms during buffer saturation and later flow within a deposition hole/emplacement room in the unlikely event of a breached canister.

Challenges when attempting to characterize flow channelling at a repository site include 1) most often, only a limited amount of data is available; and 2) the effects of channelling on mass transport on the scale of deposition holes/emplacement rooms needs to be "upscaled" to be used in larger scale groundwater flow and mass transport models.

5.1.2.2 Hydraulic Properties of Sedimentary Rock

5.1.2.2.1 Investigation of Underpressures in Sedimentary Rocks

During 2020, a new research contract was initiated with the United States Geological Survey (USGS) to continue to investigate of the anonymously low pressured shales observed within the rocks at the Bruce Nuclear site. The proposed analysis is expected to strengthen arguments regarding the possible presence (or absence) of a methane gas phase in the rocks encompassing the proposed host rock (Cobourg Formation). There are two components which will be examined through this research:

- Potential mechanisms by which the hydrogeologic system at the Bruce Nuclear site could have reached its current (pre-drilling) state with gas-phase methane present will be examined through a series of TOUGH simulations. The results will be used to better understand how pressures measured in boreholes relate to liquid pressures in the rock when a separate phase gas is present.

- The effects that a gas phase has on field-based pressure measurements will be examined. Specifically, the effects of gas-phase methane on glacio-mechanical loading and underpressure development at the Bruce Nuclear site will be investigated through a new series of TOUGH simulations to clarify which, if any, are both plausible and lead to the pressure conditions observed in the field.

During 2021, research findings from a study which used a numerical model of the Southern Ontario site to evaluate possible effects of hydromechanical coupling with multiphase methane evolution and flow on pressure evolution during a cycle of glacial loading and unloading was submitted for publication (Plampin et al., *In press*).

5.1.2.3 Numerical Methods – Groundwater

HydroGeoSphere (HGS) is a 3D integrated surface-subsurface flow and transport simulator developed by Aquanty Inc (Aquanty 2018). Currently, HGS is the reference NWMO computer code for groundwater flow and radionuclide transport simulations. In 2019, NWMO requested that Aquanty develop several new HGS features to better adapt the code to the unique modelling requirements of NWMO projects. One of the main new features is the ability to identify fracture faces based on discrete fracture network data output from MoFrac in VTK format. MoFrac is a computer code that generates realistic, structurally possible models of fracture networks based on field data (see section Numerical Methods – Discrete Fracture Networks). In addition, this new feature also allows users to assign unique property values (such as hydraulic conductivity, porosity and thickness) to each individual fracture face. Other new features are the ability to directly import 3D geology data (voxet) and 2D elevation data (tsurf) from a GOCAD (a popular 3D geology modelling tool) model into HGS. During 2021, all code development work was completed, and these new features became available for use within HGS.

5.1.3 Hydrogeochemical Conditions

Chemical and isotopic compositions of groundwater and porewater within the rock matrix provide information on residence times and evolution of deep flow systems. Information on major ion compositions of the waters, pH, and redox conditions, as well as characterization of microbial populations, support calculations of radionuclide solubility and transport, and are also relevant to assessments of the stability (i.e., performance) of engineered barrier materials such as shaft seals.

5.1.3.1 Microbial Characterization – Waters & Rocks

The microbiological organisms and their activity in any water within the rock present at the repository horizon is an important parameter with respect to the long-term behavior of engineered barriers. If sulfate-reducing bacteria are present and active in either the water or rock, there is the potential for these microbes to produce the corrosive species sulfide via sulfate reduction. While the highly compacted bentonite in the emplacement rooms is expected to prevent any microbiological activity, if sulfide is produced at the bentonite-rock boundary or further out in the far-field, there is the potential for sulfide to diffuse towards the UFCs causing corrosion. Such corrosion is currently accounted for in the NWMO's copper corrosion allowance, but it is important to include site-specific data to ensure that the corrosion allowance is acceptable and up to date with the state of the art in microbiological analysis.

As part of NWMO's site characterization activities, samples of rock, groundwater and porewater are being collected at various depths from NWMO boreholes and analyzed using methods developed through applied research at multiple Canadian universities (Waterloo, Toronto and

McMaster). These methods utilize DNA, RNA, PLFA and NMR techniques to determine the type of organisms present, the activity of these organisms, and the potential for the organisms to grow in the rock and in groundwater. To date, samples of rock and water have been collected at various depths from both the WLON-Ignace and the SON-South Bruce area. Analysis of these samples is ongoing but some initial results, published by Beaver et al. in 2021, apply 16s rRNA and culturing analysis to crystalline rock core from the WLON-Ignace area. This analysis has the capability to determine what microbes are present (if they are present) and how many of them are present. The conclusions of this early work are that microbes are not present in the rock core and therefore will have no impact on the engineered barrier system. Similar analysis on more samples from both sites will continue into 2022.

5.1.3.2 Groundwater and Porewater Chemistry in Crystalline Rock (State of Science)

New research was initiated in 2021 with the University of Waterloo that aims to provide a comprehensive review and summary of current knowledge of the chemical and isotopic compositions of fluids (groundwaters, porewaters, and gases) in deep crystalline rock settings, as well as the associated understanding regarding fluid evolution. An important emphasis of this study is on any available data from plutonic/batholith environments. The objectives are to develop a comprehensive fluid geochemistry database for relevant environs from the Canadian Shield and publication of the summary data and findings in journal articles over the course of the project. Relevant data from Canada and around the world will be considered to build a robust data collection which can be used to understand key hydrogeochemical characteristics and processes occurring in deep crystalline environs, and to compare with site-specific data from the WLON-Ignace area.

Over the course of 2021, building of the reference library for the Canadian Shield was advanced, and recruitment of a post-doctoral fellow to join the database and publication team at the University of Waterloo was accomplished. In 2022, the Canadian Shield component of the database, and a Canadian Shield fluids and associated chemistry article, will be completed for submission to journal for publication.

5.1.3.3 Measuring pH in Highly Saline Groundwaters

Hydrogeochemical research, whether it is lab- or field-based, commonly requires knowledge of the master variable, pH. pH measurements are commonly done potentiometrically, with electrodes, which is very challenging in high ionic strength ($\boldsymbol{I}$) systems, such as the brines that make up the porewater and deep groundwaters in the Michigan Basin (up to $\boldsymbol{I}$ = 8M). Spectroscopic methods offer an alternative approach for pH measurement in brines. This involves calibration of the spectroscopic properties of colorimetric indicators using specially-prepared buffer solutions, with the pH of the buffers determined by geochemical modelling. Initial work at the University of Ottawa was completed using a single indicator (phenol red) in the measurement range of pH ≈ 7 - 9. More recently, the technique has been extended over a wider range of pH (~ 3 - 9) using a multi-indicator solution. Results demonstrate that the technique is applicable up to **I** = 4M, but at higher ionic strength the sensitivity of the multi-indicator solution declines. Research is ongoing to formulate a multi-indicator that maintains sensitivity up to **I** = 8M.

5.1.3.4 Porewater Extraction Method Development

A significant area of research historically has been on development of techniques to extract porewater from the very low porosity crystalline and sedimentary rocks relevant to the Canadian program. There has been significant progress and several methods are now in use or have been recently applied as part of site characterization activities. However, techniques and approaches for the analysis and interpretation of results from porewater extraction experiments continues to be an active area of research - due to the indirect nature of these extraction procedures, as described in the following sections.

5.1.3.4.1 Porewater Extraction – Crystalline Rocks

Vacuum distillation is a well-established method to extract porewater from low-permeability sedimentary rocks (Clark et al. 2013; Al et al. 2015) for which classical methods (e.g., squeezing, centrifugation) are not always successful. During vacuum distillation, water is evaporated from a substrate under vacuum and cryogenically trapped (using liquid nitrogen) in a sample vessel. Vacuum distillation is then coupled with aqueous leaching of solutes from post-dehydrated samples to reconstruct the geochemistry of the porewaters.

The objectives of current research are to: 1) develop and optimize a method to fully extract porewater from intact crystalline core samples, and 2) benchmark the approach using suitable core material saturated with water of known isotopic composition. The primary challenge of this research to-date was development of a method to fully re-saturate the cores for benchmarking that was not accompanied by fractionation of the porewater isotopes from the original re-saturating water. To resolve this, the testing criteria for achievement have been established as: (i) complete extraction of porewater (better than 95%) to avoid isotope fractionation with the residual porewater, and (ii) measured isotope contents of the extracted porewater that are within an acceptable margin of those of the saturating water reservoir.

Several different approaches to re-saturate core were explored, some of which resulted in a either a relatively low degree of water uptake into the core samples and/or diffusive fractionation of the isotopes (left hand graph in Figure 5-5). During 2020 and 2021, re-saturation experiments using a combination of high vacuum (45 mTorr), followed by heating (120°C) at elevated pressure (15 PSI) for long durations were demonstrated to produce high levels of saturation with no significant isotope fractionation. Representative results from such high vacuum re-saturation/extraction experiments are shown in the right-hand graph in Figure 5-5.

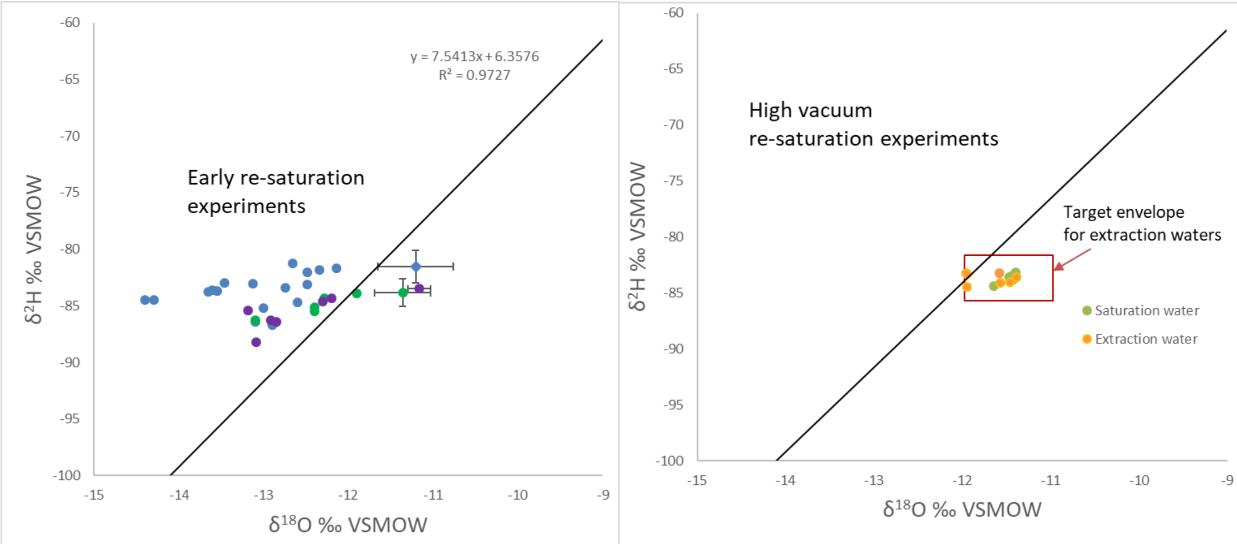


Figure 5-5: Isotopic Composition of Porewaters Extracted from Crystalline Rock. Left Chart Shows a Depletion Trend from Early Data, Attributed to the Re-saturation Process. Right Chart Shows Final Re-Saturation Protocols that Produce Porewaters Essentially Free of Re-saturation Artifacts

For porewater extraction experiments using this protocol, close to 100% of the re-saturated water mass could be recovered by distillation at 150°C (with overnight extraction under vacuum for saturated cores). Extended porewater extractions can be undertaken in two stages, assuring 100% yield for fully saturated cores, and has resulted in successful benchmarking of the method. Porewaters from fresh, fully saturated crystalline cores can be fully extracted without isotope artifacts using the extended extraction method. The isotope results indicate that this extraction procedure is quantitative and without isotope exchange or fractionation, providing an accurate measurement of the in-situ porewater isotope content in crystalline core samples.

5.1.3.4.2 Porewater Extraction – Sedimentary Rocks

Benchmarking the extraction of porewaters from the low water content and low permeability sediments of the Ordovician sequences of the Michigan basin continues to be a focus of research. Over the past year work has continued using both gravel-size (2-4mm grains) and full-size cores from the Queenston, Georgian Bay and Blue Mountain formations.

The gravel-size fraction of samples from the Bruce Nuclear site (boreholes DGR-5/6) have been leaching in deionized water for ~10 years following their original analysis by 6-hour vacuum distillation at 150°C during the initial DGR program (these are defined as 10-year gravels). In the current work, the majority of the 10-year gravel samples were extracted at 150°C for 6 hours, as well as at lower temperature (120°C for 6 hours). The purpose of the lower temperature extractions is to test whether high-fidelity isotope measurements can be achieved at a lower temperature, to further test whether any exchange between the clay hydroxyl groups and porewater might occur. Results at both temperatures show that no artefacts (enrichments or depletions in ^{18}O and ^{2}H with respect to the saturating water) were observed; extracted waters are within the range of the saturating fluid (0.5‰ for ^{18}O and 5‰ for ^{2}H). Some evidence of evaporation in the signatures are noted for both the saturating water and the extracted water, which is attributed to the 10 years of storage in plastic containers.

Full cores (whole cores) from the Bruce Nuclear site (DGR-4) equilibrated with a synthetic brine for just over 600 days were tested as part of a benchmarking exercise. In Figure 5-6, the $\delta^{18}O$ and $\delta^{2}H$ porewater values are plotted with the values measured for the saturating water (snowmelt from Ottawa) together with the values measured for equivalent-depth porewaters in DGR-5 core. The porewaters are close to the saturating snowmelt but form a trend towards the original DGR5 porewaters for these rocks. Also, a slight enrichment in deuterium exists such that the trendline falls above that of the saturating water. While geochemical exchange seems complete (measured to within about 5 percent), isotope exchange is not complete for all samples. The clear trendline towards the initial value of the porewater is evidence of incomplete exchange.

The minor enrichment in deuterium is attributed to an additional incomplete exchange for deuterium with clay waters. This reservoir is likely sampled during extraction but is not considered to greatly alter the overall porewater value. However, the preexisting deuterium enrichment from original porewaters has not likely exchanged to equilibrium with the deuterium-depleted snowmelt water, thus contributing to a slight enrichment. The much better agreement seen for the 10 year gravels suggests that over time, this reservoir would also equilibrate with a different saturating solution. Note that were this to be an artifact of hydrogen contributions from clay minerals, the effect would be the opposite, with a depletion seen in the porewaters, as observed in the Mont Terri intercomparison.

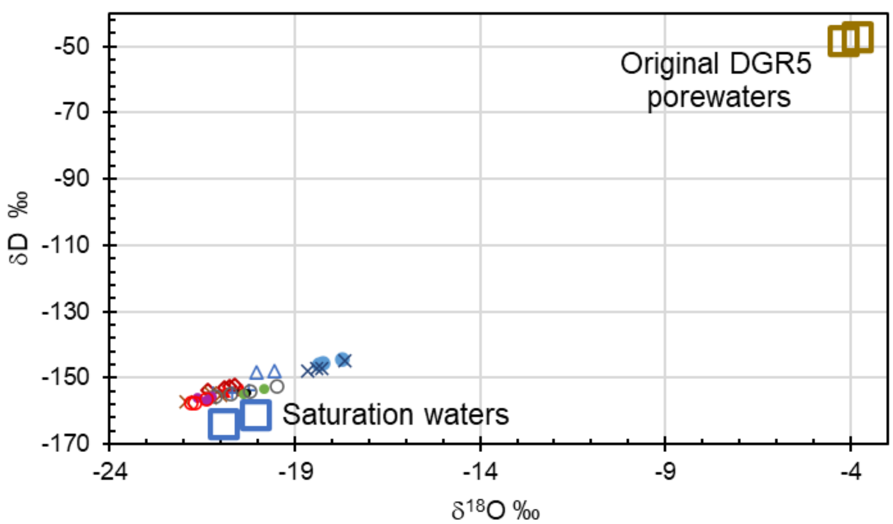


Figure 5-6: Out-diffusion was Run for 8 Weeks Before Measurements for Major Ion Chemistry Using Synthetic Porewater; Overall Concentration Ratios for Conservative Elements (Na, Cl) are Very Close to 1.0. For the Reactive Elements, Including Br (Organophilic), the Ratios were 1.11, 1.29 and 1.59 (Mg, Br, K)

Also, at the University of Ottawa, a novel method has been under development for several years to extract porewater from rock cores into cellulosic papers for subsequent analysis of the porewater composition. Recent work (2020-2021) focused on verification of the major-ion data using core samples that have been equilibrated with a known synthetic porewater composition. The experiments designed for verification of the porewater chemistry are complete and results are encouraging. The porewater concentrations determined with the paper absorption method generally compare well with the known composition of the synthetic porewater. It is especially notable that this is true not only for Cl and Br which can be determined by crush and leach, but also for the major cations Ca, Mg, Sr, Na and K.

5.1.3.5 Profiles of Li, Mg and Ca Isotopic Compositions of Porewater

Site characterization activities in low-permeability Ordovician sediments of the Michigan Basin at the Bruce Nuclear site showed that they contain Na-Ca-Mg-Cl brines (>5M) considered to originate as evaporated, post-dolomitic Silurian seawater, with residence times exceeding 400 Ma. To further constrain solute migration, this research has generated δ^{7}Li and δ^{26}Mg profiles of porewaters in these strata. Work in 2020-2021 focused on preparing porewater leachates for isotopic analysis, based on extensive pre-treatment using ion-specific column chromatography to remove interfering geochemical matrices. Efforts were focused on completing sample preparation and ICP-MS analysis, which have been greatly delayed due to lab closures during the pandemic. Magnesium isotopic measurements are carried out on a Neptune MC-ICP-MS at the Queen's Facility for Isotopic Research (QFIR). Li work was done on a Nu Plasma II MC-ICP-MS at the Geological Survey of Canada (Ottawa) and on a Neptune MC-ICP-MS at QFIR.

Interpretation of the isotope profiles for δ^{26}Mg focuses on shifts related to porewater-matrix exchange in association with dolomitization ($\uparrow\delta^{26}Mg_{pw}$), possible secondary silicate formation ($\downarrow \delta^{26}Mg_{pw}$) and possible shield-derived fluid mixing in the deep Ordovician. In addition to expanding the $\delta^{26}Mg_{pw}$ porewater dataset, measuring δ^{44}Ca in porewater will help to constrain the nature of fluid-rock interactions and potential mixing with a deep brine source in the Ordovician limestones. All samples for δ^{26}Mg and δ^{44}Ca in the porewaters have been analysed by ICP-MS for QAQC ahead of MC-ICP-MS analysis at QFIR. The final component of this work relies on the analysis of Mg and Ca isotopes in the matrix clay minerals from the Bruce Nuclear site, to be done at QFIR, which has been greatly impeded by lack of laboratory access over 2020-2021 due to the ongoing pandemic. These samples will be analysed in 2022.

Lithium is a highly soluble cation that is enriched in evaporative brines, but the isotope composition may be altered through secondary mineral formation, sorption onto clays and organics ($\uparrow\delta^{7}Li_{PW}$) or mixing with crustal fluids in the deep Ordovician sediments. Measurement of ^{7}Li in the Ordovician shales will provide further insight into the fluid-rock interactions in these formations and will be the final step in this research program. Given the large difference between the δ^{7}Li of interlayer and structural Li in clays, and that interlayer δ^{7}Li may be influenced by later changes in porewater composition, bulk analysis of the shales will not provide the most representative picture of the conditions under which these clays formed. A method for leaching the Ordovician shales to remove exchangeable Li, including interlayer Li in clays, was developed in 2020 and work continued during 2021 to isolate the structural Li in the silicates. The leached rocks and sequential leach fluids will be analysed at QFIR during 2022.

5.1.3.6 Stable Water Isotopes in Clay-bound Water

Reliable measurement of the hydrogen (H) and oxygen (O) isotope compositions of porewater entrapped in Paleozoic shales in southern Ontario presents a challenge because of the very low water-contents of these rocks and possible porewater interaction with clay minerals. There is potential for modification of original porewater H and O isotope compositions arising from: 1) exchange between porewater and structural H and O in clay minerals, and 2) O and H isotope fractionation between mobile and bound water, depending on the porewater analysis method.

Research at Western University has focused on examination of the mineralogy, and O and H isotope geochemistry, of clay minerals in Ordovician shales from the Bruce Nuclear site and nearby locations. Key findings include: 1) abundances of illite > kaolinite > chlorite comprise the <2µm fraction of these shales; 2) the clay mineral O and H isotope compositions plot to the left of terrestrial clay weathering lines in H and O isotope space; 3) calculated water O and H isotope compositions in equilibrium with these clay minerals at maximum geological burial temperature (~90°C) match porewater O and H isotope compositions measured by three techniques; and 4) apparent H isotope clay mineral-water exchange was observed in 10-week experiments at 68°C. These preliminary data suggest that isotopic exchange with structural H in clay minerals can modify porewater H isotope compositions in low water-content shales.

In 2021, progress was made to advance in the following two areas:

- A new thermogravimetric analyzer (TGA) funded by NWMO was installed in July 2021 after a lengthy, COVID-related delay. The instrument is being used to develop bound water / hydroxyl group weight loss profiles for CMS standard illite, kaolinite, chlorite, and smectite during heating (21 to 1000°C). Weight loss profiles for <2µm size-fractions of the Ordovician shales from the Bruce Nuclear site were satisfactorily reproduced at higher resolution than possible for earlier data obtained using a much older (~25-year-old) instrument. The new TGA can also be interfaced with a laser-based water-isotope analyzer (CRDS) for extraction and analysis of bound water from clay minerals. A CRDS is needed to measure bound water–mobile water O and H isotope fractionations.

- Experiments were undertaken to measure the extent of H and O isotope exchange between isotopically labelled deionized water and CMS illite, kaolinite, chlorite and smectite, and clay mineral assemblages from the Bruce Nuclear site, held at 90, 120 and 150° C for 10 weeks and 50 weeks. These experiments expanded on the preliminary H isotope exchange results reported earlier. Testing the extent of isotopic exchange that might occur both at maximum burial temperatures known for shales in this region, and for maximum temperatures reached during Vacuum Distillation Extraction of porewater, was the objective. The experiments were conducted at high water/rock ratios, in duplicate at a minimum and in quadruplicate when possible, depending on available sample quantities. All experiments were performed using clay mineral samples saturated with K^+ as the exchangeable cation. Where sample amounts permitted, the effects of Na^+ and/or Ca^{2+} as the saturating cation were also tested. The extent of isotopic exchange is not hypothesized to vary with exchangeable cation type but confounding effects from retention of residual bound water (primarily with Ca^{2+}, at least effected with K^+) could masquerade as isotopic exchange.

In addition, earlier work documenting H isotope fractionation of adsorbed water during its gradual removal from smectite was submitted for publication in Applied Clay Science (Kanik et al., *in press*).

5.1.3.7 Binding State of Porewaters – NEA CLAYWAT Project

The CLAYWAT project, launched by the NEA Clay Club, is targeted at an improved understanding of the binding state of water in the nanometric pore space of argillaceous media. In addition to a literature review of methods of potential use in this context, the project included an experimental programme on samples received from the Clay Club membership. A suite of measurements and experiments were performed by a number of laboratories, including differential thermogravimetry (TGA), differential scanning calorimetry (DSC), evolved gas analysis (EGA), mass loss upon heating to steady state at different temperatures, ad- and desorption isotherms for H_2O, N_2 and CO_2, and others. Further, nuclear magnetic resonance (NMR) relaxometry and imaging were applied to quantify porosity, pore-size distribution, to identify the relevant 1H reservoirs in the rock, to quantify diffusion coefficients for H_2O as well as to image the degree of heterogeneity of the 1H distribution in the samples.

As of 2021, a significant portion of the report is available in draft form (including results and method-specific discussion), and two abstracts were submitted for presentation at the 2022 Clay Conference. The general discussion and the conclusions are in progress. The plan is to finalise the report in 2022, following a peer review by the Clay Club and potentially external experts.

5.1.3.8 Porewater Residence Times: Noble Gases

The isotopic analysis of heavy noble gases in porewaters within preserved cores was initiated to complement helium isotope studies performed as part of geosphere model development for the Bruce Nuclear site. In recent years, the functionality of the Helix multi-collector noble gas mass spectrometer has been improved through upgrades to the noble gas purification and separation line. The noble gas laboratory at the Advanced Research Complex is the only one in Canada with instrumentation for analysis of the isotopes of helium together with the higher-mass noble gases, and the ingrowth of geogenic noble gases, including ^{4}He, ^{21}Ne, ^{40}Ar and ^{136}Xe, which can be used as measures of groundwater and porewater age. Over the past two years, a refined method for heavier noble gas separation was advanced to improve the selective trapping of Kr and Xe, and to avoid the loss of Kr when sequentially trapped on the stainless steel in-line with a more aggressive activated charcoal trap. A polished stainless steel wool trap was found to improve the Kr signal 35-fold. The greater sensitivity on the instrument, resulting from improvements to gas separation on the sample preparation line, have provided high quality data. It is anticipated that determination of the ingrowth of the higher-mass noble gas isotopes above their atmospheric ratios will provide robust chronologies of the porewaters in this system, which will be complementary to the He, CH_4, and ^{87}Sr chronometers that have already been developed during characterization activities.

Observations from archived core samples from the Bruce Nuclear site, after 10 years of preservation, have suggested that many of the samples have degassed into the vacuum-sealed aluminum foil packaging over time. For many, this gas contains the same isotopic ratios of methane as those originally measured for adjacent core samples during site characterization activities. Gas samples have been taken from several of these long-preserved cores, and core crushing conducted for porewater content and water isotopic analysis. From these archived samples, a ^{136}Xe excess has been discovered from select samples, with an average $^{136}Xe/^{130}Xe$

value of 2.24. This finding is a demonstration of the enrichment that should be observed if the porewaters are as old (>260 Ma) as suggested by the helium isotope work. These results were assessed together with uranium concentrations in these rocks to calculate the length of time for this ^{136}Xe accumulation in comparison with He data for these samples. The results of this work, over several method development and analysis steps from 2019-2021, was submitted and approved for journal publication in 2021 (Zuo et al. 2021).

5.1.3.9 Porewater Gases - Mont Terri PC-D Experiment

The NWMO is currently leading the Porewater Gas Characterization Methods (Non-inert and Noble Gases): Field and Laboratory Methods Comparison (PC-D) Experiment at the Mont Terri URL. The objectives of the experiment are to: 1) compare results obtained for gas concentrations and isotopes using different methods used by various nuclear waste management organizations to assess the comparability of different methods for homogeneous rock cores extracted from within the same shale unit (lower shale facies in the Opalinus Clay), and 2) assess the data from various approaches to determine if alternative (short-term or novel) methods can yield satisfactory results for site characterization needs in potentially less time than the current standard out-gassing approach employed by numerous researchers and laboratories around the globe for the purpose of gas characterization.

Over the course of 2020, due to delays associated with the global COVID-19 pandemic, emphasis was placed on experimental planning and establishing a drilling contract for an experiment-specific borehole. In September 2021, the PC-D borehole (BPC-D1) was drilled, parallel to being in the lower shale facies, with five regularly spaced sampling intervals over its 20-m length. Samples for noble and non-inert gases were collected adjacent to one another in each sampling interval for the three participating laboratories (Hydroisotop GmbH, University of Ottawa and GFZ Helmholtz – supported by BGR), as well as complementary samples for porewater chemistry analytics (to be run using the absorptive paper method). The analytics, data compilation (which includes the review and comparison of any previous noble and non-inert gas data from within the lower shale facies in other experiments at the URL) and overall findings of the comparison study are anticipated to be ready for publication in a Mont Terri Technical Report in 2023.

5.1.3.10 Mont Terri Geochemical Data (GD) Experiment

The NWMO is a partner in the Geochemical Data (GD) Experiment at the Mont Terri Underground Research Laboratory (URL) in Switzerland. The GD Experiment aims to collect and evaluate data from various activities in the URL, in terms of assessing coherence with the established porewater conceptual model for system evolution. Open questions that are identified in the model(s) or in the understanding of behaviour often become targeted research projects within GD (e.g., lab investigations, in-situ measurements and/or modelling activities). In 2021, work as a part of GD was focused primarily on two key projects: 1) carbonates in clay rocks, and 2) redox and the role of Fe-containing minerals in controlling system Eh. Additional work is planned on the assessment of trace elements in porewaters (provided there is sufficient support for the work) in 2022.

5.1.4 Transport Properties of the Rock Matrix

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, to provide representative estimations of long-term system behaviour. The following research programs contribute to the NWMO's technical capabilities in the context of assessing long-term solute mobility and retention.

5.1.4.1 Permeability

Recent research at McGill University focused on the estimation of the permeability of cuboidal blocks of granite obtained from Lac du Bonnet (western flank of the Canadian Shield) and from Stanstead (eastern flank of the Canadian Shield). The surface patch permeability test developed by Selvadurai (2010) and documented by Selvadurai and Selvadurai (2010) for the testing of Indiana Limestone was adopted and modified to test the cuboidal granite samples. The surface permeability was extrapolated to the interior regions using a kriging technique and a computational approach was used to estimate the permeabilities of the granites in three orthogonal directions. The experimental procedures are documented by Blain-Coallier (2020) and findings from this research are reported by Selvadurai et al (2020).

5.1.4.2 Diffusion Properties

5.1.4.2.1 Method Development – X-ray CT Imaging

The University of Ottawa acquired an X-ray CT system in 2016, and it has been tested extensively to assess its capabilities to improve imaging capabilities in low-porosity rock and to optimize measurement parameters for tracer experiments. The monitoring of iodide and cesium diffusion in crystalline rocks was advanced in 2020, and the instrument was modified during 2020-2021 to allow X-ray spectrometry in order to minimize the effects of beam hardening and increase signal-to-noise ratios for improved tracer detection.

The spectrometry system is operated in two modes, X-ray absorption in transmission mode and X-ray fluorescence. The X-ray absorption approach has been used successfully to monitor iodide and cesium diffusion in Queenston Fm shale and the data demonstrate that beam hardening effects are virtually eliminated. The X-ray fluorescence technique is currently being developed and preliminary results indicate that it has potential for experimental monitoring of diffusion and reaction processes with a diverse range of tracers that are of interest for evaluation of transport and attenuation properties in the near field.

5.1.4.2.2 Mont Terri Diffusion Experiments – DR-B, DR-E, CI, and CI-D

The NWMO is a partner in the DR-B long-term diffusion experiment in undisturbed Opalinus clay, the DR-E long-term diffusion experiment in the fault zone, the CI long-term cement-Opalinus clay interaction experiment, and the CI-D diffusion across 10-year-old concrete/claystone interface experiment at the Mont Terri URL.

The objectives of the DR-B experiment are i) to develop a means for the long-term monitoring (>10 years) of in-situ iodide diffusion process at a large scale in a clay formation; and ii) to validate the diffusion process understanding developed and transport parameters determined through previous experiments. The experimental setup consists of a central borehole and 3 surrounding observation boreholes. Sodium iodide (NaI) solution was injected in the central borehole in April 2017 and is expected to diffuse over time toward the observation boreholes. Starting in November 2018, a breakthrough of iodide in the observation borehole located closest to the injection borehole was observed. The iodide concentration in the observation boreholes has been measured regularly (Jaquenoud et al. 2021).

The DR-E experiment investigates tracer migration (including diffusion) in the main fault zone within Opalinus clay. The experimental setup includes two injection boreholes for multi-tracer solutions (including cations, anions, neutral species), one borehole will target the central part of the main fault zone, and the second one will target the upper boundary zone of the main fault zone. The objectives of the experiment are i) to investigate tracer migration (including diffusion) within the fault zone of Opalinus clay over long time period to provide effective transport properties of radionuclides for safety assessment calculations; ii) to determine if self-sealing and healing mechanisms of clay within fault zones apply as expect; and iii) to investigate if enhanced anisotropic permeabilities with respect to undisturbed shale zone are present.

The CI long-term (> 10 years) experiment is intended to complement the current knowledge on the influence of cement on Opalinus clay and bentonite. Three types of cement are used in the experiment: ordinary Portland cement (OPC) and two types of low-pH cement (LAC and ESDRED). The objectives of the CI-D experiment are i) to assess the impact of the long-term (10 years) cement-Opalinus clay interface reactions (CI experiment) on diffusion of solutes (^{3}H and ^{36}Cl); and ii) to provide in-situ data for reactive transport modelling. The CI-D experiment setup consists of a borehole filled in 2007 with three different types of concrete (OPC, LAC and ESDRED) and compacted bentonite (MX-80) (borehole for the CI experiment), an injection borehole, and monitoring boreholes. High pH fluid circulation started in July 2018, and tracer (^{3}H, ^{36}Cl) injection has started since May 2019. The CI-D experiment is expected to last for 3 – 4 years. An international joint CI/CI-D modelling team is modelling the alteration due to cement-clay interaction and the tracer transport across such interfaces with different reactive transport codes including MIN3P-THCm.

5.1.4.3 Sorption

Sorption is a mechanism for retarding sub-surface radionuclide transport from a DGR to the environment. The NWMO has initiated the development of a sorption distribution coefficient (K_d) database for elements of importance to the safety assessment of a DGR (Vilks 2011). This initial database was further developed to include sorption measurements for Canadian sedimentary rocks and bentonite in saline solutions (with ionic strength I = 0.23-7.2 M) including a reference porewater SR-270-PW brine solution (Na-Ca-Cl type with I = 6.0 M) (Vilks and Yang 2018).

Researchers at McMaster University continues to systematically study the sorption properties of Se, Tc, U and Eu on limestone, shale, illite and bentonite (MX-80) in SR-270-PW brine solution, as well as on crystalline rocks and bentonite in a reference groundwater CR-10 (Ca-Na-Cl type with I = 0.24 M) under reducing conditions. The effects of ionic strength and pH on Se and Tc sorption on shale, illite, limestone, bentonite and crystalline rocks have been investigated (e.g., Goguen et al. 2021; Walker et al. 2018, 2021; Racette et al. 2019;). It was found that sorption of Se(-II) on illite and MX-80 showed little ionic strength dependency across the ionic strength range of 0.1-6 M. Sorption of Se(-II) on shale at low ionic strength (0.1 M and 0.5 M) were higher than those at higher ionic strength of 1-6 M. One journal paper documenting Se(-II) sorption on granite and MX-80 bentonite in CR-10 was submitted in 2021.

A new research program was initiated in 2021 to study the sorption of Pd on biotite, quartz and feldspar in Ca-Na-Cl saline solution using batch experiments, sorption modeling and DFT (Density Function Theory) calculations. Quartz and feldspar are the main mineral components of granite, whereas biotite is a common but minor mineral component of granite which is considered to dominate the sorption of some radionuclides. The measured sorption K_d values will be used to update the NWMO sorption database for use in the safety assessment.

5.1.4.4 Surface Area & Cation Exchange Capacity

In 2018, the University of Bern completed research to characterize external surface area (BET) and cation exchange capacity (CEC) in sedimentary rock cores from the Bruce Nuclear site. Samples from the Queenston, Georgian Bay, Blue Mountain and Collingwood Member formations were evaluated (rock types included claystone, marl and limestone). The research focused on addressing the question of mineralogical fractionation induced by sieving to different grain sizes (i.e., can a specific fraction for geochemical experiments be used and the results considered representative of the whole rock?), as well as the effect of crushing on determined CEC values (e.g., does crushing create new mineral surfaces, and is it permissible to extrapolate geochemical data obtained on disintegrated or crushed material to the intact rock?).The main findings are summarized below:

1. Chemical and mineralogical compositions do not vary systematically between grain-size fractions, indicating that size reduction and sieving do not lead to a resolvable fractionation (with the exception of the limestone sample).
2. BET surface area increases with decreasing grain-size fraction by 50 – 100% (claystone and marl) and 300% (limestone). Crushing to smaller particle sizes, thus, provides access to surfaces that are inaccessible or not present in the intact rock.
3. CEC of claystone and marl samples increase by 7–31% between fractions 1–4 mm and <0.063 mm. While crushing to smaller grain size creates new surfaces, these are predominantly related to minerals with a small or negligible CEC, such as carbonates or quartz. It is concluded that the effect of grain size plays a relatively limited role for CEC.
4. CEC of the limestone sample between fractions 1–4 mm and <0.063 mm increases by 110%. Care needs to be taken when extrapolating data produced on crushed limestone samples to the intact rock.
5. Good linear correlations can be found between clay content, BET surface area and CEC. BET surface measurement can be used as a proxy of the cation-exchange capacity of the sample, which is a feature known for other sedimentary rocks.

The results of this work were compiled into a Technical Report for the NWMO in 2019. A modified version of the final report is anticipated to published by the NWMO in 2022.

5.1.5 Geomechanical and Thermal Properties

5.1.5.1 In-Situ Stress

The in-situ stress state is a fundamental parameter for the engineering design and safety assessment of a DGR. Obtaining reliable estimates of in-situ stress is important, however, this is often hindered by small numbers of field stress measurements as well as by variability arising from the geological environment. Bayesian data analysis applied to a multivariate model of in-situ stress can potentially overcome these problems and generate a multivariate stress tensor for a site. In 2020 together with SKB (Sweden), NWMO initiated a new research program at the University of Toronto to investigate the use of Bayesian data analysis in the statistical quantification of in-situ stress variability. Recently developed, novel techniques are being applied to the analysis of site-specific data provided by SKB, with the objectives of (i) generating design stress tensors for the site and (ii) developing protocols suitable for application at other sites.

This new research project on quantification of in situ stress began in July 2020. The two conference contributions on dealing with heterogeneity of in situ stress listed below were made during 2021 (Javaid and Harrison 2021a,b). Furthermore, a conference paper abstract on Bayesian regression of in situ stress with depth was accepted for EUROCK 2022, and the writing of the manuscript of this paper is in progress. In addition to the heterogeneity of in situ stress and the Bayesian regression model, the development of a Bayesian hierarchical model for in situ stress was initiated during 2021. Analysis of extensive in situ stress data from the Forsmark site, Sweden, began.

5.1.5.2 Rock Properties from Laboratory Experiments

5.1.5.2.1 Thermal Properties

The thermal conductivity characteristics of the Cobourg limestone was estimated using a multiphasic approach for the estimation of the lighter species containing predominantly calcite and dolomite and the darker regions containing, calcite, dolomite, and a clay fraction. The spatial distribution of the nodular fractions was determined by previous research that investigated the effective permeability of the Cobourg limestone by dissecting a cuboidal sample (Selvadurai, 2019a). The research that investigated the estimation of the effective thermal conductivity of the Cobourg limestone was documented by Selvadurai and Niya (2020). A research program was initiated to determine the thermal conductivity characteristics of the Lac du Bonnet Granite. In September 2021, this experimental research project was transferred to a new doctoral student.

5.1.5.2.2 Poroelastic Properties

A key poroelastic parameter relevant to the constitutive modelling of fluid saturated rocks with an elastic skeletal behaviour is the Biot coefficient that defines the partitioning of externally applied stresses between the porous skeleton and the pore fluid. A critical experiment used in these investigations relates to the estimation of the compressibility of the solid phase composing the porous fabric, during applications of an isotropic stress. To perform the experiments required for the estimation of the Biot coefficient, the pore space must be completely saturated with no influence of any trapped air. When the permeability of the rock is extremely low, as in the case of the Cobourg limestone, the estimation of the solid phase compressibility by saturation is less reliable and time consuming. In the research conducted in connection with the Cobourg limestone, the compressibility was estimated by appeal to the mineralogical composition of the rock and a widely accepted multiphasic theory (Selvadurai, 2019b; Selvadurai and Suvorov, 2020; Selvadurai et al, 2020). The same procedures were applied to estimate the effective compressibility of the solid phase of the Lac du Bonnet granite. Estimates for the Biot coefficient for the Lac du Bonnet granite are documented in a journal article published by Selvadurai (2021).

5.1.5.2.3 Effect of Temperature on Mechanical Properties

The alteration of the thermal, hydraulic, and mechanical (THM) properties of the Lac du Bonnet granite subjected to extreme heating up to 90 degrees Celsius and possibly higher (150 degrees Celsius) is being examined at McGill University. This research was originally planned to begin in 2020 but was delayed, in part due to the pandemic. A new Ph.D. project was initiated during 2021 and includes the thermal conductivity measurements of the Lac du Bonnet granite as described in the Section 5.1.5.2.1 above.

5.1.5.3 Rock Properties from In-Situ and/or Large-Scale Experiments

5.1.5.3.1 POST Project

The overall aim and scope of the POST2-project were described and presented at on-line EUROCK 2021 conference (Jacobsson et al. 2021). Also during 2021, previous measurements to assess the normal stiffness of the large direct shear testing machine were evaluated (Larsson 2021a), which enables compensation for system deformation to be made when direct shear tests under constant normal stiffness (CNS) condition are performed. The procedure follows the previous work done for the small direct shear testing machine.

In addition, direct shear tests of six large rock joint granite specimens, 300 × 500 mm, were conducted. Two specimens with a natural joint were tested under constant normal load (CNL) condition and four with a tensile induced joint were tested, two under CNL condition and two under constant normal stiffness (CNS) condition. The results of the experiments will be evaluated during 2022.

The issue with the poor control of the shear actuator, as previously reported (NWMO, 2020), was solved before the shear tests were carried out. Some modifications of the specimen holder between the different test batches were necessary to improve the performance of the experiments. Acoustic emission measurements were carried out during the experiments. However, some problems with signal disturbance from external sources were obtained which destroyed the results of several measurements. The acoustic emission measurements, financed by RISE, are outside the POST2-project.

The work done in the associated PhD-project about scale effects, with partial funding from Swedish rock engineering research foundation (BeFo), resulted in a Licentiate thesis presented in April 2021 (Larsson 2021b).

5.1.5.3.2 Mont Terri FE-M Project

The FE-M experiment, long-term monitoring of the full-scale heater test, continues with the heating phase which commenced in December 2014. This experiment was designed to demonstrate the feasibility of: (1) constructing a full-scale 50 m long and 3 m in diameter deposition tunnel using standard construction equipment; (2) heater emplacement and backfilling procedures; (3) early post-closure monitoring to investigate repository-induced coupled thermo-hydro-mechanical (THM) effects on the backfill material and the host rock (i.e., Opalinus Clay); and (4) validation of THM models.

Field measurements are on-going include temperature, pore-water pressure, humidity/water content and suction, thermal conductivity, deformations, and stresses. The program is currently focused on the long-term monitoring of the THM processes confirming the technical readiness of the conceptual modelling framework pertinent to assessment of the long-term performance in the near field scale. Nagra has established a THM modelling task force consisting of Technical University of Catalonia (UPC), the École Polytechnique Fédérale de Lausanne (EPFL), and BGR/TUBAF/UFZ. In 2020, modelling activities continued as part of subtask 1.1, which comprises code and calculation verification of TH and THM model results amongst the three teams which used Code_Bright, Code_Aster and OpenGeoSys, respectively.

This task was nearly complete by the end of 2020, with only final refinement calculations to be undertaken in early 2021 by one modelling team. Notably, a versatile calculation and verification approach has been developed by the Task Force (TF), which includes questionnaires, comprehensive yet flexible code-to-code or code-to-measurement assessment strategy, and rigorous evaluation metrics. Subtask 1.2, which involves back-analyses of FE monitoring data was also initiated during 2020.

5.1.5.3.3 Mont Terri GC-A Experiment

The main objective of this experiment is to understand the geomechanical in-situ response of the Opalinus clay during excavation at the transition from shaly to sandy facies. This experiment consisted of multiple components including:

- Monitoring of the excavation convergence and pore pressure response,
- Laboratory and field geophysical measurement of static and dynamic elastic properties of the Opalinus clay, and
- In-situ stress measurements.

Activities in GC-A focus on continued 1) monitoring of pore pressures and convergence measurements in Niche 2; and 2) detailed interpretation of pressure meter tests conducted to measure in-situ stress by the University of Alberta. During 2021, an abstract was published at the 6th International Conference on Geotechnical and Geophysical Site Characterization held in Budapest in 2021 (Liu et al. 2021).

5.1.5.3.4 Shear Induced Pore Pressure Around Underground Excavations

A new Ph.D. research project, co-funded by NWMO and Nagra, was initiated at the University of Alberta in 2020. The overarching objective of this research is to advance the understanding of the coupled hydro-mechanical processes that occur during underground excavations in heavily overconsolidated clays and weak rock-like shale deposits.

Previous field tests completed at Mont Terri Underground Rock Laboratory (Mont Terri) established that deformations around underground openings in Opalinus Clay are highly dependent on the direction of the excavation relative to the materials bedding. Excavations completed in a direction parallel to the materials bedding have shown higher pore pressures, yielding at relatively small strains compared to laboratory results, and larger than predicted deformations. This research program examines these findings through two mine-by experiments completed at Mont Terri, one parallel and one perpendicular to the materials bedding, where instruments were strategically placed in front of and around the tunnel’s excavation zone. The findings from these experiments will then be compared to the results of a laboratory testing program. The laboratory program utilizes a novel direct shear apparatus that is being developed at the University of Alberta. This apparatus will be the first to incorporate micro fibre optic pressure sensors (MFOPs) into a direct shear test to measure the pore pressure response along the shear zone of the sample while applying a strain-controlled boundary condition.

During 2021, research advances for laboratory work included 1) the construction and commissioning of a triaxial device that utilizes a microfibre optic sensor installed inside of a sample to compare external pore pressure measurements to a local internal measurement during testing; and 2) and the construction and commissioning of a one-dimensional consolidation device that is able to apply up to 20 MPa of force to a sample. Advances for the field component include the gathering and processing of in-situ field measurements and the creation of three 3D elastic isotropic models of tunnel excavations completed at the Mont Terri Rock Laboratory using the program FLAC3D. These initial models are being compared to the in-situ pore pressure measurements through a stress analysis that is then converted to pore pressure using Skempton's B value.

5.1.5.3.5 Field Trials of a New Tool for In-Situ Stress Measurements: Reservoir Geomechanics Pressuremeter

In 2021, NWMO joined with Nagra to provide support for their field trial of the University of Alberta's Reservoir Geomechanical Pressuremeter (RGP), a novel new tool for determining in-situ stresses and shear stiffness in sedimentary formations. Nagra's field trial was completed in December 2021. Nagra and NWMO are sharing information on the field campaign, including experience gained, testing results, and comparisons of the RGP results to results from other field tests (e.g., Hydrofracturing) and/or laboratory tests conducted by Nagra and used to verify the RGP measurements. This research agreement also includes the participation of Nagra personnel and information sharing for a field trial of the RGP by NWMO.

5.1.5.4 Numerical Modelling of Geomechanics

5.1.5.4.1 Rock Mass Effective Properties

Starting in 2016, POSIVA, SKB, and NWMO jointly sponsored a research program with ITASCA Consultants s.a.s. (ICSAS) and the Fractory (Joint Laboratory between ICSAS, CNRS and the University of Rennes, France) to improve our understanding of the role played by the fractures on rock mass mechanical behavior. In order to overcome the limitations of the available rock mass classification systems, numerical modelling using a Discrete Element Method is done with the final goal of developing guidelines a numerical tool (PyRockMass) for upscaling the mechanical properties of a rock mass containing Discrete Fracture Network (DFN). During this first phase of the project (Phase 1), numerical modelling and mechanical testing of Synthetic Rock Mass (SRM) specimens (Min and Jing 2003, Esmaieli et al. 2010, Mas Ivars et al. 2010; Harthong et al. 2012; Le Goc et al. 2014; Le Goc et al. 2015; Poulsen et al. 2015) were largely used to support the project fundamentals and applied developments, as it is not possible to perform laboratory tests of rock mass samples with dimensions compatible with DFN scales.

Theoretical developments relative to elastic properties, specifically specimen scale effective elastic properties and stress distribution below the specimen scale achieved during Phase 1 created the foundation used to define a DFN-based rock mass effective properties methodology. The derived method predicts the change in elastic properties of a rock mass (Young's modulus and Poisson's ratio in simple cases and more generally all the terms of the compliance tensor), relatively to intact rock conditions, the embedded DFN model (geometry and fracture mechanical properties), scale of interest and remote stress conditions. The method is analytical and thus eliminates computational burden and numerical limitations inherent to rock mass numerical modelling. It also provides a means to understand which characteristics of the fractured system (i.e., DFN model) are critical for the mechanical behavior, and to relate these DFN model metrics to rock mass properties with simple relationships (Davy et al. 2018). An application to the Forsmark site FFM01 Fracture Domain was published in Darcel et al., 2018. To reproduce the project results and apply it to new cases, core functionalities were implemented in a Python program referred to as PyRockMassTool. PyRockMassTool computes the equivalent compliance tensor of a rock mass specimen defined from a DFN description of the fracture system embedded in the rock.

The same scientific approach described above - fundamental theorectical developments, use of numerical modelling, testing and methodology development – are being applied to Phase 2 of this research, which was initiated as a joint project between SKB and NWMO in 2020. The main objectives of Phase 2 of are to further test the methodology application for elastic conditions, and to develop a fundamental understanding of the relationship between DFN model properties, stress fluctuations and rock mass effective strength. The basis of the approach (i.e., relationships between remote stress, local stress and fracture normal and shear displacement) will be also used to provide individual fracture apertures, as a prerequisite for hydromechanical coupling and flow modelling.

During the first half of 2021, the project task on the prediction of the proportion of critically stressed fractures (CS) was pursued and completed. The approach and modeling assumptions build on the work initiated in Davy et al. (2018). A fracture is identified as critically stressed if the critical shear stress, beyond which it switches to a slipping regime, is reached. The capacity of the method to identify which are the key controlling factors of the CS state among a Discrete Fracture Network (DFN) population is demonstrated. Several sensitivity analyses are performed, with one based on the impact of the stress depth dependency. The second one focuses on which part a DFN is more critically stressed, in term of size range or orientation set. Finally, a comparison based on an analytical development is performed to evaluate if the dilation term due to critical state is significant compared to the fracture normal closure.

The second main task undertaken during 2021 was to advance understanding and quantification of the stress fluctuations in a fractured system using DFN models embedded in a rock matrix and loaded with remote stress conditions. The presence of the fractures in the rock induces stress variations. The aims of the task are to first quantify the stress fluctuations, in term of spatial and intensity variations and to define sound indicators of these variations; and secondly, to relate the indicators to the properties of the DFN. Von Mises stresses, and stress dispersion coefficients (Gao and Harrison 2016, 2018a, b) are considered, together with a participation ratio (Davy et al. 1995) to quantify the localization. The analytical development is supported by numerical simulations of Synthetic Rock Masses into which fractures are embedded. The numerical modelling is done with 3DEC, and a relationship to relate the global stress dispersion to the DFN parameters has been established.

5.1.5.4.2 Determination of Biot and Skempton Hydromechanical coefficients for fractured rock masses (BIKE)

This study aims at quantifying the Biot and Skempton coefficients for fractured rock masses. The project began at the end of 2021 with a task on the *Formalization of the coupled Hydro-Mechanical (HM) behavior for fractured media*. A literature review was done to first discuss the meaning of Biot's and Skempton's coefficients in porous homogeneous rocks. Successively we reviewed the current state-of-the-art focusing on extending the poroelasticity concepts to anisotropic porous materials and fractured rocks. The outcome of this task is to propose a way to estimate Biot's and Skempton's coefficients for a single fracture, which will be used later for the definition of these coefficient at the scale of the rock mass.

5.1.5.5 NSERC Energi Simulation Industrial Research Chair Program in Reservoir Geomechanics

In 2019 NWMO joined the renewal of a multi-sponsor NSERC/Energi Simulation Industrial Research Chair (IRC) in Reservoir Geomechanics at the University of Alberta. This IRC chair aims at advancing experimental and numerical methods as well as field studies to help mitigate operation risks and to optimize reservoir management as they pertain to the coupled processes in oil and gas reservoirs. Some of the findings are expected to be also applicable to crystalline settings.

Overall, participation in this multi-faceted IRC program is expected to advance our understanding of how intact rock and fractures at various scales respond to thermal-hydro-mechanical processes associated with a DGR. The first annual research symposium was held in February 2021. This symposium provided sponsors with progress updates on all key research areas underway as part of the program.

5.2 LONG-TERM GEOSPHERE STABILITY

5.2.1 Long-Term Climate Change Glaciation

5.2.1.1 Surface Boundary Conditions

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

Following the update to the GSM methodology and subsequent validation, a new phase of research is in progress with the goal of refining the representation of the evolution of paleolakes and surface drainage basins within the model, as well as further analyses of fits to relative sea-level data in Southeastern Hudson's Bay region. Additional modelling capabilities to University of Toronto GSM are currently being developed to deliver improvements to simulations of Laurentide ice sheet evolution. During 2021, the two main advances in the development of GSM were:

4. Incorporation of latest PISM-based ice dynamical core, with fully coupled proglacial lakes.
5. Development of graphical and postprocessing scripts for representing surface drainage results.

In addition, results from research conducted investigating the possible contributions from the Fennoscandian or British Isles ice sheets to a Henrich event (H3) which is known to have originated in Hudson Strait were published by Velay-Vitow et al. (2021).

5.2.1.2 Glacial Erosion of crystalline rocks

Since late 2019, research has been underway at Dalhousie University to study the effects of glacial erosion within crystalline bedrock settings. A key outcome of this research will be a state-of-the-science review of published information relating to glacial erosion in crystalline bedrock settings. This review includes consideration of i) recent advances in theoretical work on glacial erosion; ii) erosion studies involving numerical modelling of ice sheets; iii) any prior erosion rates from studies in the Canadian shield and other areas with similar lithology and glacial histories; iv) synthesis of factors that control glacial erosion and a ranking of their relative importance for crystalline bedrock settings in Ontario; v) descriptions and applications of cosmogenic radionuclides or other emerging approaches or measurement techniques to provide estimates of erosional processes and erosional rates and; vi) detailed sampling strategies for cosmogenic nuclide methods, as well as any special considerations for associated field and laboratory work.

In mid-2020, a postdoctoral fellow was on-boarded to Dalhousie University and work on the state-of-science review began. During 2021, two draft journal publications were prepared based on the findings of this research. It is anticipated that both articles will be submitted for publication during 2022; one of the two articles will be published as an invited paper to Earth Science Reviews.

5.2.1.3 Glacial and Proglacial Environment – Numerical Modelling

5.2.1.3.1 CatchNet Project

CatchNet (Catchment Transport and Cryo-hydrology Network) is a joint international program formed by international nuclear waste organizations and cold region hydrology researchers (URL: https://www.skb.se/catchnet/). It was established in 2019 to advance our understanding of hydrological and biogeochemical transport processes for a range of cold-climate conditions in the context of long-term, deep geological disposal of used nuclear fuel. CatchNet has identified three research packages (RP) to address important knowledge gaps:

- RP1: connecting the glacial and sub-glacial hydrology with the periglacial hydrological system on landscape scale;
- RP2: permafrost transition periods;
- RP3: biogeochemical cycling.

Currently, CatchNet has three full members (SKB, NWMO and RWM) and one supporting member (COVRA). Each full member funds a PhD student or postdoctoral fellow to work on a research topic related to cold-climate conditions.

NWMO is supporting a PhD student based at McGill University. This PhD program started in September 2020 and the research topic is to examine the impacts of permafrost transition on surface and subsurface hydrologic processes (RP2).

5.2.1.3.2 University of Montana – Joint Research with SKB

In 2019, NWMO and SKB initiated a project to support researchers at the University of Montana (USA) to study coupled ice sheet, groundwater, and surface water hydrological processes through new data analysis and numerical modeling. This modelling study uses the field data previously collected from two international projects (GAP and GRASP) in the Kangerlussuaq area of western Greenland. This joint project has focused on the following two main areas:

- Evolution of the thermal state of the ice sheet bed;
- Ice-sheet processes influencing the ice sheet - bedrock boundary and underlying groundwater pressures near the ice sheet margin.

The researchers work closely with the CatchNet program, participating in the CatchNet annual meeting and other activities regularly. In particular, the results of this study will be used as boundary conditions by CatchNet RP1.

During 2021, much of the data analyses was completed. A journal article documenting the response of Greenland’s groundwater system to ice sheet change was published by Liljedahl et al. (2021). A second journal article examining the generation of basal meltwater under the Greenland ice sheet. was published (Harper et al., 2021), and a third publication on this research was submitted to the Journal of Glaciology and is currently in review (Saito et al, submitted).

5.2.2 Groundwater System Stability and Evolutions

5.2.2.1 Numerical Modelling Approaches

Reactive transport modelling is a useful approach for assessing long-term geochemical stability in geological formations. Reactive transport modelling is used to assess: 1) the degree to which dissolved oxygen in recharging waters may be attenuated within the proposed host rock; 2) how geochemical reactions (e.g., dissolution-precipitation, oxidation-reduction, and ion exchange reactions) may affect groundwater salinity (density) and composition along flow paths; and 3) how diffusive transport of reactive solutes may evolve in low-permeability geological formations.

Unstructured grid capabilities were implemented into the multi-component reactive transport code MIN3P-THCm for 3-dimensional (3D) systems, including the parallelization of the unstructured grid functions (Su et al. 2020; Su et al. 2021). A 3D demonstration simulation based on a hypothetical sedimentary basin is underway for the evaluation of MIN3P-THCm code capabilities for large-scale 3D flow and reactive transport simulations using unstructured meshes. The specific purpose of this work is to evaluate the effect of dimensionality (2D versus 3D) on the development of flow patterns and solute transport in sedimentary basins during a glaciation cycle. A journal article is in preparation with anticipated submission in 2022. MIN3P-THCm was applied to investigate the formation mechanisms for sulfur water observed in the Michigan Basin (Xie et al. 2018). The simulations have been further improved using a more complete and realistic geochemical network including ferrous and ferric iron and associated redox and mineral dissolution/precipitation reactions. Simulated results show improved agreement with the available field data. The impact of paleo-glaciation on the formation and distribution of elevated sulfide is also being investigated through reactive transport simulations. A journal paper documenting the improved reactive transport simulation of sulfur water is expected to be submitted in 2022.

5.2.2.2 MICA – Michigan International Copper Analogue project

The Michigan International Copper Analogue (MICA) project was initiated in early 2021 and originally involved NWMO, RWM, SKB, Nagra and the Geological Survey of Finland (GTK). In July of 2021, BGE signed on as full partners for Phase I. The purpose of the MICA project is to provide evidence of the behaviour of metallic copper on geological timescales. The internationally renowned copper deposits of the Keweenaw peninsula, USA, will be studied to ascertain both genesis and evolution - and by extension stability - in response to changing conditions such as Eh, pH, groundwater chemistry, temperature, presence/absence of oxygen, etc. The knowledge gained could be considered subsequently by waste management organizations in relation to the stability of copper on long timescales. The project may also enhance the robustness of a safety case that considers a disposal concept that uses metallic copper as part of the engineered barrier system, concerning, for example, the persistence of metallic copper under certain geochemical conditions that could be experienced by an evolving deep geological repository in certain environments. Such knowledge could be used in subsequent work to evolve the disposal concept, or to initiate further research activities. This project is managed by the Geological Survey of Finland (GTK) and various technical experts.

Phase I is set to wrap up mid-2022 and will provide a comprehensive, state-of-the-science review report, including a catalogue of available relevant samples, a description of the known geologic history of each sample, information on environment(s) of exposure (including timing and length(s)), identification and planning of analytical research and some preliminary analyses as proof of concept. In late 2021, 9 samples were analysed using a combination of SEM, XCT, and Laser Ablation to identify corrosion products, corrosion processes, and process rates. Other methods will be explored for Phase II to attempt to unravel the relevant geological history of each sample to correlate environment(s) of exposure with the resulting corrosion products, processes, and rates.

Also in 2021, the MICA project plan was presented at the safeND conference in Germany (Liebscher et al., 2021). The MICA project is anticipated to comprise at least 2 phases. Phase II will be the main research phase on selected Keweenaw-based natural analogues from Phase I; specific testing will be decided after Phase I is complete.

5.2.3 Seismicity

5.2.3.1 Regional 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. 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. 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.

A technical report submitted to NWMO in late 2020 summarizes operational statistics and additions to the earthquake catalogue for the year 2019 and was published at the end of 2021 (Ackerley et al. 2021). During 2019, 35 earthquakes were located in the northern Ontario study area (Figure 5-7), ranging in magnitude from 1.2 to 3.3 m_N. The pattern of seismicity generally conformed to that of previous years. The largest earthquake was an event at 15 km depth, north of Kapuskasing. There were no felt earthquakes in the study area in 2019.

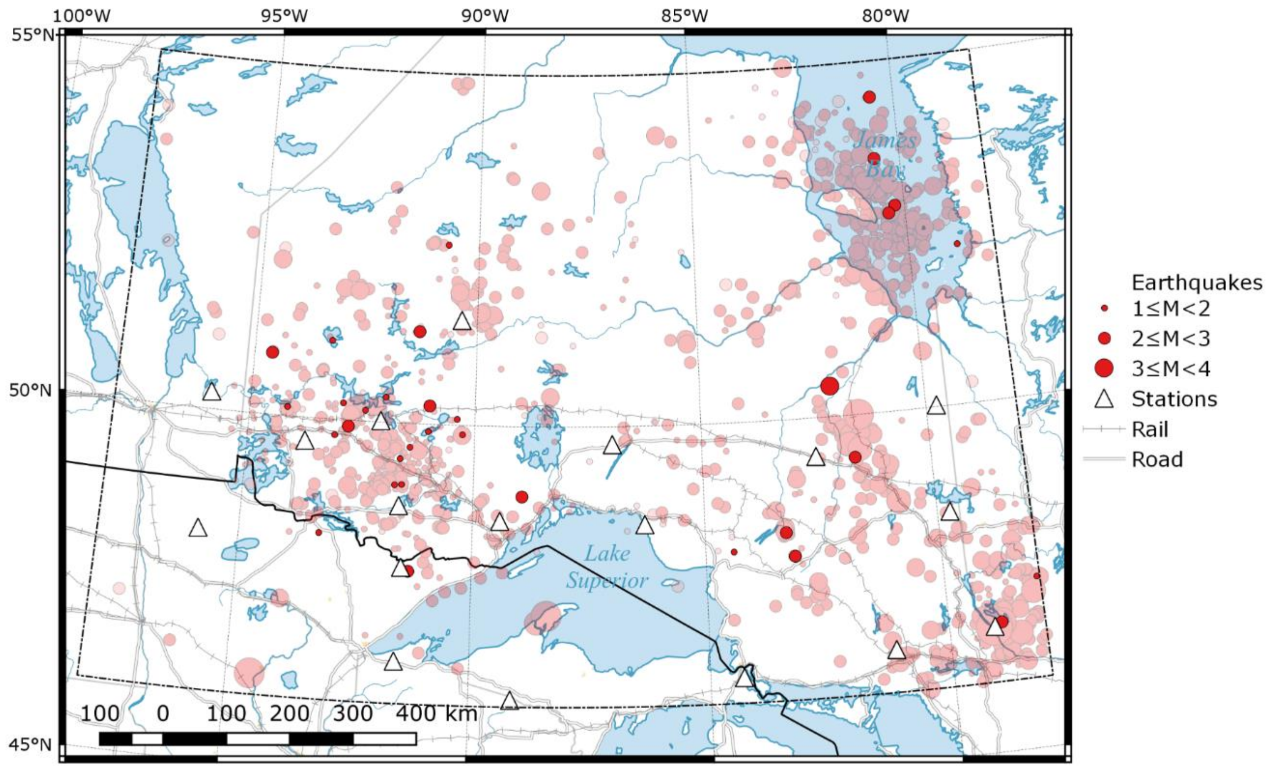


Figure 5-7: Earthquakes in Northern Ontario, 2019. Events in 2019 Have Black Outlines, while Events from 1900–2018 are Plotted Semi-transparently and Have Grey Outlines. Events and Stations are Plotted in the Study Area Only. The Study Area is Outlined with a Dash-dotted Line. Only Stations with Data Available in 2019 are Shown (Ackerley et al. 2021)

5.2.3.2 Mont Terri Nanoseismic Monitoring (SM-C) Experiment

The NWMO is involved in the Mont Terri Nanoseismic Monitoring (SM-C) Experiment, which serves as a comparative tool for the NWMO microseismic monitoring program. As noted in the 2020 ATR, specific objectives were achieved in 2020 (1. continual micro-seismic monitoring of the Mt Terri facility and its surrounding region; 2. identify the source mechanism and structure associated with the recorded seismicity and 3. produce an earthquake catalogue for all events down to 0.0ML). In 2021, the experiment continued, with emphasis on recalibration and data processing.

5.2.3.3 Paleoseismicity

Due to the long-life cycle of a repository, potential perturbations from ground motions associated with rare strong earthquakes requires consideration. No such earthquakes have occurred in Ontario in human-recorded history. However, the NWMO is carrying out research to look for evidence, or absence of evidence, of such events in the past as described below.

During 2020, new research project with the Geological Survey of Canada in Ottawa was initiated focusing on i) developing criteria to objectively distinguish between neotectonic and glaciotectonic faulted sediments; and ii) assessing the inferred neotectonic origin of the Timiskaming East Shore fault. Similar reconnaissance profiling was also carried out in Tee and Kipawa lakes, Quebec. This research continues to build on work that began in 2012 and is aimed at providing an understanding of seismicity over time frames dating over the Holocene. Additional results from this earlier phase of research were published (Brooks et al., 2021) on a mass transport deposit, interbedded within glaciolacustrine deposits of Lake Ojibway which was discovered using a sub-bottom profile survey at Frederick House Lake, Ontario.

Over the duration of this research project from 2020 to 2023, the scope of the research includes:

6. Investigating the distribution and character of the mass transport deposits generated by the 1935 M_w6.1 Timiskaming earthquake, Timiskaming area, Quebec; and
7. Distinguishing neotectonic versus non-neotectonic faulting within the glaciolacustrine deposits in the Lake Timiskaming basin, Ontario-Quebec

Restrictions associated with the pandemic during 2020 prevented initiation of the sub-bottom acoustic profiling and overwater hammer seismic surveys planned in the Temiskaming area and on Lake Timiskaming, respectively. This caused a critical delay in the data collection needed to address the two project components during the first year of this project. This field work was rescheduled to 2021 and cores were collected from the Timiskaming area. Radiometric dating of these cores suggests that mass transport deposits identified within them are likely the product of subaqueous failures triggered by the 1935 Temiskaming earthquake. Further work in the region is schedule for 2022..

5.2.4 Geomechanical Stability of the Repository

5.2.4.1 Excavation Damaged Zones

The Queen's Geomechanics Group has been investigating the mechanics of, and developing predictive and characterization tools for, Excavation Damage Zone (EDZ) evolution around deep geological repositories in sedimentary and crystalline rock. Past research focussed on fundamental mechanics of EDZ, damage threshold definition, detection in laboratory testing, prediction and assessment of EDZ using continuum models, and secondary effects such as time dependency and saturation. More recently, new geomechanics simulation approaches have been developed and adapted by Queen’s to allow for deeper mechanistic investigation of EDZ evolution. In parallel, Queen’s research has updated conventional testing and investigation tools and developed new protocols for characterization. The focus for 2021 was on preparing the research basis for upgrading protocols (and eventually standards) in key rock mechanics testing activities, identifying key sensitivities and, in some cases, limitations of common testing practice, as well as delving into the validity and verification challenges with modern (commercially available) discontinuum and coupled software for geomechanics analysis.

The primary role of the Queen's Geomechanics Group is to improve the routine use of these advanced tools for the specific purpose of EDZ analysis in the DGR context and to develop protocols and guidelines for optimized model construction, calibration, verification, and interpretation. These advanced tools, however, also require advancements in the way that lab-scale testing and field sampling and logging is carried out. Current work is aimed at improving and upgrading techniques for physical investigation of discontinuum components and property definition using the previously standardized compression, tensile, confined strength, and direct shear testing methods (including boundary condition implications).

The testing laboratory emerged from Covid limitations in mid-summer with activities returning to normal. Hegger et al. (2021a, b) published research on an innovative strain monitoring and mapping approach for rock test samples. Innocente et al. (2021) completed research on developing a practical approach to ultra-long-term strength prediction for rock. Research to explore boundary conditions and data processing approaches for direct shear testing was published (Packulak et al. 2021) and research is now progressing on improving the understanding of testing mechanics and appropriate simulation (for EDZ purposes) involving rocks with variable levels of mechanical anisotropy. Significant advances in our understanding of multi-stage shear testing for rock discontinuities were made and published as part of the GEONiagra – CGS conference during 2021 (MacDonald et al. 2021a,b) and will be finalizing publications on these findings in 2022. MacDonald et al. 2021c have been investigating the effect of confining stress, boundary conditions and sample damage on sonic velocities in rock – leading to a better understanding of the discrepancies between lab- and field-derived elastic properties =. Gaines has completed an exhaustive study to develop the most robust approach for the determination of EDZ damage parameters (CI and CD).

On the modelling and numerical simulation front, Fischer and Diederichs. 2021a,b have published on the comparison and reconciliation of discontinuum simluations for excavavtion damage and those achieved (as in the past) with equivalent continuum approaches. Markus et al. 2021 and Markus and Diederichs (2021) are laying the groundwork for an exhaustive review of coupled continuum/discontinuum models for excavation seepage and effective stress calculations. Co-leads of the QGGG, Diederichs and Day (2021) published an exploratory paper highlighting the sensitivities of EDZ predictions to the discrete modelling of rock fabric elements.

5.2.4.2 Repository Design Considerations

5.2.4.2.1 Analysis of Shaft and Cavern Stability

The excavation of the underground openings (i.e., including placement rooms, shafts) for a repository, and the subsequent backfilling with heat-emitting UFCs as well as the buffer material, will induce coupled THM processes in-situ. NWMO has been conducting numerical analyses at near- and far-field scales to enhance our understanding of the response of the rock mass to hypothetical Canadian DGR configurations in both sedimentary and crystalline settings (ITASCA 2015). These studies considered perturbations induced by the repository as well as the natural processes expected during a 1 Ma period. In the study by ITASCA (2015), the THM processes were one-way coupled, whereas a recent THM modelling study (also by ITASCA) employed fully coupled THM analyses using refined input parameters. The sensitivity of the model predictions to some uncertain model input parameters (e.g., block-to-contact stiffness ratio for discontinuum modelling, poroelastic properties, and rock mass permeability) were also investigated. NWMO's review of the final technical report on this research was on-going during 2021.

Once site-specific DFN information is available, similar analyses will be conducted to support repository engineering and design, as part of a complementary study during detailed site characterization.

5.2.4.2.2 Fault Rupturing

ITASCA has completed a research project with NWMO to numerically simulate a sizable seismic event resulting in the mobilization of surrounding fracture networks. Rupture of a seismogenic fault and its effect on the deformation of the off-fault fractures were examined. The purpose of the analysis was to determine the off-fault fracture displacements to inform the selection of respect distance within the repository horizon in crystalline rock.

Three different models were constructed to accommodate the fault size for moment magnitudes (Mw) of 6.1, 6.6 and 6.9 seismic events occurring at the end of the glacial cycle when the vertical stress due to ice sheet is zero but glacially-induced horizontal stresses still remain. This base case analysis was conducted for five DFN realizations developed from the structural geology of Forsmark, Sweden. The modelling results revealed that for an earthquake with a moment magnitude, Mw of 6.1 and a dip angle of 40° (base case), the fault average shear displacement during the slip is about 1.6 m and the maximum shear displacement along the fault is 3.4 m. No DFN fractures slip more than 5 cm were observed in all DFN realizations except for a fault dip angle of 30°. Increasing the event magnitude while maintaining a dip angle of 40° (base case) resulted in a greater number of off-fault fractures with slippage over the 5 cm criterion and an increase in the distance to the fractures with such large displacements. NWMO's review of the final technical report on this research was on-going during 2021.

Once site-specific DFN information is available, similar analyses will be conducted to support repository engineering and design, as part of a complementary study during detailed site characterization.

5.2.5 Geoscientific Studies in Support of Geosynthesis

5.2.5.1 Natural Resources Assessment

A hydrocarbon resource assessment for southern Ontario was produced for the NWMO by the Geological Survey of Canada (Alberta Office) and published in 2021 (Chen et al., 2021).

The resource assessment was comprised of two parts, an assessment of unconventional shale oil/gas resource potential in the organic-rich shales of the Collingwood Member of the Cobourg Formation and the Blue Mountain Formation within the Huron Domain of southern Ontario; and a quantitative assessment of conventional hydrocarbon potential within the Cambrian, Ordovician and Silurian strata of the Huron Domain of southern Ontario.

These represent an update of previously published work (Bailey and Cochrane 1984a &b; Golder, 2005), including the addition of supplemental information related to recent pool discoveries, history, size, and cumulative production rates. The results demonstrated that the geographic distribution of the predicted hydrocarbon resources of the Upper Ordovician

Collingwood and Rouge River shale units, indicate that a large volume of the potential hydrocarbon resources of these two shale units occur in the Appalachian Basin portion of southern Ontario).

Only a small quantity of the reservoir-risked resource is predicted to occur in the potential repository area within the Huron domain of southwestern Ontario. The bulk of the potential hydrocarbons that are estimated to be trapped within the members is considered to be exceptionally low in the study area due to a combination of low permeability, contrasting lithologies, low formation pressures, low degrees of thermal maturation, high oil viscosity impeding hydrocarbon fluid flow, and poor oil show index S1/TOC <1. When compared to similar analogous black shales, the Collingwood and Rouge River Members (combined) show a density (M BOE/sq km) that is several orders of magnitude lower than other oil producing shales, highlighting their unsuitability as an economic resource.

6 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 2021 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 2017) and the sedimentary rock of the Michigan Basin in southern Ontario (NWMO 2018). The reports summarize key aspects of the repository concept and explain why the repository concept is expected to be safe in these locations (see Table 6-1).

Table 6-1: Typical Physical Attributes Relevant to Long-term Safety

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

6.1 WASTE INVENTORY

6.1.1 Physical Inventory

Currently there are about 3.1 million used CANDU fuel bundles. Based on the known plans for refurbishment and life extension, there could be about 5.5 million used CANDU fuel bundles (about 106,400 Mg heavy metal) from the current generation of nuclear power (Gobien and Ion 2021).

The CANDU fuel bundles are a mature product, with small design variations over the years primarily in the dimensions and the mass of each bundle, as well as variations in the number of elements per bundle by reactor type. The 37M bundle recently introduced in some stations has slightly different dimensions compared to the previous standard bundle.

In addition to the CANDU used fuel, AECL also has ~500 Mg of prototype and research reactor fuel fuels in storage at the Chalk River Laboratories and Whiteshell Research Laboratories. Most of this is UO_2 based fuel from the Nuclear Power Demonstration (NPD), Douglas Point and Gentilly-1 prototype reactors. AECL also holds a small amount (i.e., less than ~100 Mg) of various research fuel wastes with a variety of compositions and enrichments. There is also a very small amount of fuel still in service in low-power research reactors at McMaster University, Royal Military College of Canada and Polytechnique Montréal.

The Canadian used fuel inventory and forecast are updated annually by NWMO (Gobien and Ion 2021). A database with key information on fuel bundles produced to date is maintained by NWMO.

6.1.2 Radionuclide Inventory

An update of the reference CANDU radionuclide inventory was completed in 2020. Calculations were carried out using the most recent Industry Standard Tool version of the ORIGEN-S code and the latest CANDU specific nuclear data (e.g., cross-sections, decay data, and fission product yields) for a range of used fuel burnups of interest to the safety assessment or design. A report documenting the updated inventory and thermal power as a function of decay time for a reference CANDU fuel bundle was published (Heckman and Edward 2020).

In 2021, a short-term leaching and dissolution study on a prototype used fuel bundle was completed, providing experimental data supporting NWMO’s current CANDU fuel inventory and instant release fractions databases (see Sec. 6.2.3).

6.1.3 Chemical Composition

Measured data on main and trace elemental composition from 21 unirradiated CANDU fuel bundles (UO_2 pellets, Zircaloy end caps, Zircaloy tubing, Zircaloy tubing with a braze and spacer, and Zircaloy tubing with CANLUB coating), which encompassed a range of manufacturers, bundle types and manufacture dates, was previously completed to support the development of a recommended elemental composition value for UO_2 pellets and Zircaloy cladding (which includes the tubing as well as end caps, braze region and CANLUB).

Additional analysis was completed in 2020, which expanded the material composition database and improved the method detection limits of select elements. In particular, the additional analysis focused on nitrogen and halogens in the fuel and Zircaloy cladding, and protactinium in the fuel, which are potential precursors of activation products.

6.1.4 Irradiation History

The NWMO maintains a statistical summary of the key parameters for the large majority of used CANDU fuel bundles: bundle type, source reactor, date of discharge, burnup and peak linear power. Burnup is important for determining the radionuclide content of a fuel bundle. Peak linear power is a secondary parameter that has small effect on radionuclide inventory, however it provides an indicator of the peak temperatures reached in the fuel. This in turn is relevant for the nature of the fuel microstructure and assessing the radionuclide distribution within a fuel pellet.

The Canadian stations all operate within a consistent set of operating conditions, so have similar irradiation history. The burnup and peak linear power distributions for CANDU fuel discharged from the Bruce, Pickering and Darlington nuclear stations were determined for 1970 to 2006 (Wilk and Cantello 2006), up to 2012 (Wilk 2013) and up to 2019 (Lampman 2021). The typical burnup of CANDU fuel ranges from about 130 to 220 MWh/kgU, with a median burnup value from about 170 to 200 MWh/kgU between the stations. The 95th percentile values vary between about 220 MWh/kgU and 290 MWh/kgU (Lampman 2021).

Lampman (2021) estimates burnup and peak linear power, for periods where the data is not readily available in electronic format, and incorporates this data in the distributions of burnup and peak linear power. The population of estimated data represents less than 10% of the current fuel bundle inventory.

6.2 WASTEFORM DURABILITY

6.2.1 Used Fuel Dissolution

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.

Research on UO_2 dissolution continued at Western University to further understand the mechanisms of a number of key reactions, such as the influence of H_2O_2 decomposition and the reactions of the fuel with H_2 produced either radiolytically or by corrosion of the steel vessel. The mechanistic understanding of the corrosion of UO_2 under used fuel container conditions is important for long-term predictions of used fuel stability (Liu et al. 2017a, 2017b, 2017c, 2018, 2019). A study on the kinetics of H_2O_2 decomposition on SIMFUELs (simulated spent nuclear fuels; doped UO_2 specimens containing noble metal particles) has been conducted to determine the influence of noble metal particles on the reactions of H_2O_2 with UO_2 (i.e. UO_2 corrosion and H_2O_2 decomposition) by a combination of electrochemical, surface analytical and solution analytical methods (Zhu et al. 2019). It was observed that > 98% of the H_2O_2 was consumed by H_2O_2 decomposition.

The study of the kinetics of H_2O_2 decomposition has been extended to standard CANDU fuel pellets to investigate variations in fuel reactivity due to differences in the manufacturing process. The characteristics of a series of standard UO_2 pellets (1965-2017) has been investigated using electrical resistance measurements and Raman spectroscopy. Experiments on H_2O_2 decomposition on the standard UO_2 pellets are underway.

The kinetics of H_2O_2 reduction on SIMFUEL, RE^{III}-doped UO_2 and non-stoichiometric UO_2 have been conducted using standard electrochemical methods at rotating disk electrodes. It was found the rate of H_2O_2 reduction decreased in the order of SIMFUEL > Gd-doped UO_2 > Dy-doped UO_2 with the rate suppressed on the RE^{III}-doped $UO_{2.}$ The slightly faster rate on the SIMFUEL may be attributable to the catalysis of reduction on the noble metal particles. The H_2O_2 reduction on all three specimens was found to be suppressed by the presence of the ground water anion HCO_3^-/CO_3^{2-} (Zhu et al. 2020). The results of the research on the kinetics of H_2O_2 reduction on SIMFUEL and RE^{III}-doped UO_2 will be presented in a journal publication.

The H_2 effect in suppressing the corrosion behavior of UO_2 (un-doped and RE^{III}-doped UO_2) without catalysis of noble metal particles has been studied by producing H radicals electrochemically and radiolytically to simulate radiation effects on UO_2 corrosion when H_2 is present (Liu et al. 2021). It was observed that the combination of gamma radiation and H_2 was required to reduce the UO_2 matrix, and the reduction of U^V was reversible for specimens close to stoichiometric (UO_{2+x} with $x < 0.005$) but only partially reversible for RE^{III}-doped UO_2 with a much higher U^V content. At high gamma dose rates and dissolved H_2 concentrations the matrix reduction appeared to be irreversible.

A state-of-the-art review has been conducted in 2021 to review the basic properties of CANDU nuclear fuel, how they are changed by in-reactor irradiation, and how these changes influence fuel behaviour inside a failed waste container in a DGR. The review includes studies conducted on UO_2 (pellet/powder), SIMFUELs, alpha doped UO_2, and spent fuel. The results of the review will be published in 2022.

6.2.2 Solubility

The maximum concentration of a radionuclide within or near a failed container will be limited by the radionuclide solubility. Radionuclide solubilities are calculated by geochemical modelling using thermodynamic data under relevant geochemical conditions. These data are compiled in quality-controlled thermodynamic datasets.

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 VI of the project from February 2019 to January 2023 will provide (1) an update of the chemical thermodynamics of complexes and compounds of U, Np, Pu, Am, Tc, Zr, Ni and Se with selected organic ligands, (2) a review of the chemical thermodynamics of lanthanides, and (3) a state-of-the-art review on thermodynamics at high temperatures.

The reviews of molybdenum thermodynamic data, ancillary data, the state-of-the-art reports on the thermodynamics of cement materials and high-ionic strength systems (Pitzer model) are underway.

The NEA TDB project provides high-quality datasets. This information is important, but is not sufficient on its own, as it does not address the full range of conditions of interest. For example, the NEA TDB project has focused on low and moderate salinity systems in which activity corrections are described using Specific Ion Interaction Theory (SIT) parameters. The SIT model is most useful in ionic strength up to 3.5 molal (Grenthe et al. 1992). Due to the high salinity of porewaters observed in some deep-seated sedimentary rock formations in Canada, a thermodynamic database including Pitzer ion interaction parameters is needed for radionuclide solubility calculations for sedimentary rock environment.

The state-of-the-art report on high-ionic strength systems (Pitzer model) will be useful to identify the data gap for Pitzer ion interaction parameters. The THEREDA (THErmodynamic REference DAtabase) Pitzer thermodynamic database (Altmaier et al. 2011) is a relevant public database for high-salinity systems. It has been assessed by the NWMO and found to provide a good representation of experimental data for many subsystems.

The NWMO is also co-sponsoring the NSERC/UNENE Senior Industrial Research Chair in High Temperature Aqueous Chemistry at the University of Guelph, where there is capability to carry out various thermodynamic measurements at high temperatures and high salinities. This Chair program initiated in 2016. Progress has been made in several areas: (1) the equilibrium constants for uranyl complexes with sulfate at high salinities from 25 to 350 ºC have been determined by Raman spectroscopy approach (Alcorn 2019). These are the first measurements to be reported at 350 ºC; (2) the equilibrium constants for uranyl complexes with chloride at high salinities from 25 to 300 ºC have been determined by Raman spectroscopy approach; (3) the equilibrium constants and transport properties of lanthanum with chloride at high salinities from 25 to 250 ºC have been determined by Raman spectroscopy and conductivity approach; and (4) participating in the NEA TDB project to lead the state-of-the-art review of experimental methods and thermochemical databases for actinides, lanthanides and other selected elements at high temperature and pressure relevant to nuclear waste management. One journal paper documenting the thermodynamic properties of uranyl chloride complexes and two papers on the formation constants and transport properties of lanthanum chloride complexes are expected to be submitted in 2022. The structures of all the species identified by Raman spectroscopy have been confirmed by computational work using Density Functional Theory (DFT) methods. The lanthanum chloride conductivity results provide the first definitive thermochemical and transport property data over this temperature range and are expected to serve as a model system for estimating the properties of other Ln^{3+} and An^{3+} aqueous chloro-complexes.

The NWMO updated the database of radionuclide solubility for Canadian crystalline rock environment (Colàs et al. 2021). The radionuclide solubility limits were calculated in a reference groundwater CR-10 (Ca-Na-Cl type with TDS = 11 g/L) under three scenarios: 1) groundwater directly enters the canister without interacting with the bentonite buffer or the canister materials; 2) groundwater interacts with the carbon-steel container prior to contacting the used nuclear fuel waste inside the container; and 3) groundwater interacts with both bentonite buffer and carbon-steel container prior to contacting the used nuclear fuel waste inside the container. The effect of temperature on the solubility was evaluated at four different temperatures (15°C, 25°C, 50°C and 80°C) in each scenario. In 2021, the radionuclide solubility limits at Canadian sedimentary rock conditions were calculated in a reference groundwater SR-290-PW (Na-Ca-Cl type with TDS = 287 g/L) representing the groundwater geochemical conditions at the repository depth of Canadian sedimentary rocks under three scenarios as in CR-10. The results will be published in a technical report in 2022.

6.2.3 Radionuclide Release

This topic area encompasses the processes by which radionuclides or chemically toxic elements are released from used CANDU fuel. This can only occur once a container fails, and the fuel is contacted by groundwater.

Studies of the interaction between used fuel and groundwater done over the last 30 years have established that radionuclide releases occur via two primary mechanisms acting on different time scales. These mechanisms are known as “instant release” and “congruent release”.

Instant release is the relatively rapid release of a small percentage of the inventory of those radionuclides (such as isotopes of Cs, I and Xe) that reside in the fuel-sheath gap and at the fuel grain boundaries. These nuclides can be quickly accessed by water once the fuel sheath fails. The second and much slower process is the congruent release of the radionuclides from the UO_2 fuel matrix, which occurs as the fuel grains corrode or dissolve.

In 2021, a short-term leaching and dissolution study on a prototype used fuel bundle was conducted to determine the fuel inventory and instant release fractions. The experimental results support NWMO’s current CANDU fuel inventory and instant release fractions databases.

6.3 BIOSPHERE

6.3.1 General Approach – Post-closure Biosphere Modelling and Data

The biosphere is a complex system, that will evolve over the one-million-year timescales considered in a safety assessment. In the context of deep geologic repositories, biosphere models are developed to derive potential dose and non-radiological consequence by calculating constituent of potential concern (COPC) concentrations in the biosphere and considering dominant or representative pathways.

In 2021, the NWMO continued the development of a new system modelling tool known as the Integrated System Model or ISM (Gobien and Medri 2019). One of the components of the ISM tool is a dynamic biosphere model, ISM-BIO which was implemented using the AMBER software. The model simplifies the biosphere as a series of compartments which can each receive, accumulate, and transfer contaminants. Transfer between some compartments is dynamically modelled, while others are modelled by ratios that assume the compartments are in quasi-equilibrium over the time scales of interest. In the model, the calculated COPC environmental concentrations are then used to calculate the dose to stylised human receptors by applying dose coefficients and lifestyle-specific exposure rates. The ISM-BIO will continue to evolve in an iterative approach as the sites are characterized and the assessment objectives evolve.

6.3.2 Participation in BIOPROTA

BIOPROTA is an international collaborative forum 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 radioactive waste management practices. Overall, the intent 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. The NWMO is one of the sponsoring organisations of the Transport of C-14 in the Biosphere project initiated in 2021.

<u>Transport of C-14 in the Biosphere Project</u>

The primary objective of the project is to investigate the use of new conceptual models for the transport and distribution of C-14 releases from geological disposal facilities for solid radioactive wastes. The scope of the project includes literature review on the biogeochemical cycle of carbon, development of conceptual models, and development of preliminary mathematical models for terrestrial, freshwater, and marine environments. The literature review and the development of conceptual models were completed in 2021. A final report for the study is expected to be published in 2022.

6.4 SAFETY ASSESSMENT

6.4.1 Screening

Used nuclear fuel stored in the repository will contain hundreds of different isotopes arising from fission, neutron activation and decay processes. However, there is huge range in both the concentration and in the hazard of each of these various species (radionuclides or chemical elements). In 2021, the NWMO completed a radiotoxicity and screening analysis (Gobien et al. 2021) whose purpose was to quantify the hazard associated with used CANDU fuel and determine which radionuclides and chemically hazardous species in the fuel are of highest consequence for more detailed analyses.

Gobien et al. (2021) details the data supporting the hazard and screening assessments, the results of the hazard assessment as well as the methodology and results of the screening assessments. The hazard assessment considered the fuel activity and radiotoxicity, and the screening assessments identify radionuclides and chemically hazardous elements of consequence to pre-closure, post-closure, human intrusion, and non-human biota assessments.

The radionuclides and chemically hazardous elements identified in Gobien et al. (2021) will be considered in more detailed safety analysis in future.

6.4.2 Pre-closure Safety

The pre-closure period includes site preparation, construction, operation, decommissioning, monitoring and closure. Topics include normal operations safety (public and worker dose), and malfunctions and accidents. In the context of a geological repository and related facilities for used fuel, these topics were addressed as part of AECL's Environmental Impact Statement (AECL 1994, OHN 1994), and reviewed as part of the NWMO options study (NWMO 2005). The pre-closure safety assessment will be updated in parallel with the ongoing work to develop more detailed plans for operations and surface facilities.

6.4.2.1 Normal Operations

A preliminary dose assessment of the facility was carried out in 2014 to guide ALARA (As Low As Reasonable Achievable) development of the repository concepts (Reijonen et al. 2014).

A preliminary study was completed in 2021, to estimate the potential radiological impact to the public and the non-nuclear energy workers (non-NEW) from normal operation of the DGR and its related surface processing facilities. A conceptual design of the DGR was considered, and a generic site was assumed for this study. During normal operations, airborne radioactivity could be released during handling of the used fuel from surface contamination that is generally present on used fuel bundles and from cladding failures in the fuel element. Waterborne emissions could result from cell washdowns and decontamination of used fuel modules, used fuel transportation packages, and containers. The potential radiological doses to the public were estimated assuming potential airborne and waterborne emissions as well as the direct and skyshine external radiation doses from used fuel to public or non-nuclear energy worker (non-NEW) receptors were also estimated. Simple conservative models were used to estimate the dispersion of airborne and waterborne emissions. The study assumed exposure to receptors at a few locations, including a potential fenceline location. Radiological doses to the public were calculated using the methodology described in the Canadian Standards Association (CSA) N288.1-14 (CSA 2014) for a reference case, as well as sensitivity cases used to bound uncertainties associated with input parameters. The initial results from this study, which will inform the further development of the conceptual DGR design, indicate that the surface facilities can be designed and operated to ensure that members of the public are safe, and provide directions for optimization of the design basis.

A preliminary assessment of the radon hazard was completed in 2020, to determine whether there is health hazard to workers during construction and operation of the DGR, and a need for radon monitoring or development of any action levels in order to be in compliance with the applicable regulatory requirements. The study was conducted for a generic crystalline or sedimentary rock site. The results of the study, published in Liberda (2020), indicate that there is no significant radon hazard to the workers or the general public during construction and operation of the DGR. For workers, the highest radon concentration in an area where workers may be present is in the ventilation exhaust shaft. The concentration of radon in all worker locations is less than the Derived Working Limit of 200 Bq/m^3, based on the Canadian Guidelines for Management of Naturally Occurring Radioactive Materials (unrestricted classification). For members of the public, even those very close to the facility, the dose contribution from radon during construction and operation of the facility is much less than from natural sources indicate that there is no significant radon hazard to the workers or the general public during construction and operation of the DGR.

6.4.2.2 Abnormal Events and Accidents

A preliminary study was carried out to identify potential internal accident scenarios that may arise during the operations phase for the repository, based on a conceptual design of the UFPP and repository (Reijonen et al. 2016). In this preliminary study, a failure modes and effects analysis (FMEA) was used to identify potential internal hazards resulting from, for example, failure of equipment, failure of vehicles, failure of the shaft hoist system, loss of electric power, ventilation and filtration system failure, and human error. The estimates of the internal initiating event frequencies were obtained based on data from the nuclear industry and from earlier used fuel management studies (AECL 1994). The potential external events were also identified for a generic site based on literature review.

A preliminary analysis was completed in 2020, assessing the potential public dose consequences for the accident scenarios identified in the previous hazard identification study (Reijonen et al. 2016) for a generic site. The recent study considered exposure to a person standing at various distances from the fence line under conservative atmospheric conditions. Atmospheric dispersion factors were derived based on the Gaussian dispersion model described in CSA N288.2-M91 (CSA 2003). Radiological doses to the public were calculated for accidents classified as Possible Events (occurring at least once every 100 years of operation) or Unlikely Events (occurring less frequent than Possible Events). The presence or absence of ventilation system High Efficiency Particulate Air filters was also considered in combination with specific accident scenarios. The preliminary results indicate that the calculated public doses for inhalation, air immersion and ground exposure pathways remain below the interim dose criterion for all accidents considered. This study also looked at the minimum site boundary distance by calculating public doses at various distances from the UFPP, Ventilation Shaft, and Main Shaft. Sensitivity cases were carried out to determine the effect of stack release height, the effluent exit velocity, and the release orientation on the calculated minimum site boundary distance.

The potential external hazard events are dependent on the site. In 2021, a study was initiated to identify the external hazard events at the two DGR study areas in Ontario. Using a structured approach, the potentially hazardous events and accident scenarios that could result in an increase in radiological consequence during the operations of the DGR facility are identified. The external natural and non-malevolent human-induced hazards are assessed using the evaluation methodologies outlined in the CNSC regulatory documents REGDOC-2.1.1 and draft REGDOC-2.4.4. This study, which continues to 2022, does not include the external hazards that are addressed by other NWMO work and studies, notably the seismic hazard and the precipitation-based flood hazard. The work related to the seismic hazard potential is assessed under site characterization. The potential impact of climate change on flood risk is considered given the operating timeframe for the repository and is described below.

6.4.2.3 Climate Change Impacts Study

A study was initiated in 2018 to review anticipated climate change impacts on climate conditions (e.g., temperature and precipitation) and develop a methodology to incorporate these climate changes into probable maximum precipitation (PMP) estimation appropriate for the DGR study areas in Ontario. A report documenting the study was published in 2019 (Wood 2019).

The preferred method by Wood (2019) was applied to assess the climate change impacts on the PMP, Intensity-Duration-Frequency (IDF) curves, and snowpack accumulation projections for both the WLON-Ignace and the SON-South Bruce areas. The approach follows the key steps in Figure 6-1. Of these steps, the approach to evaluating future climate impacts on precipitation uses the state of science and publicly available climate projections to complete the climate change impact assessment on the PMP and the IDF values.

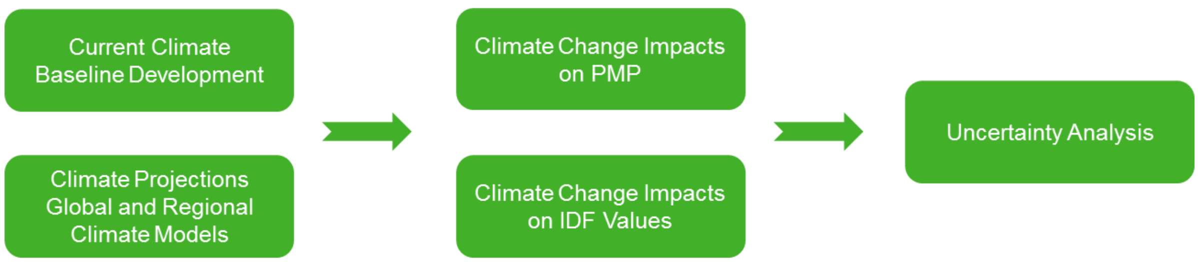


Figure 6-1: High Level Stepwise Approach in Climate Change Impacts Study

The multi-model ensemble approach was used to describe the probable range of results and potential climate changes to PMP and IDF amounts expressed as percentiles, so that the level of acceptable risk can be selected by using the desired percentile. Both studies considered projected changes in climate over three time periods: mid-century (2041 to 2070); end-of-century (2071-2100); and beyond 2100. These periods coincide with the different phases for a possible deep geological repository, including site preparation and construction; the operational period; extended post-closure monitoring; and decommissioning. There is a level of inherent uncertainty when projecting future climate; however, the approach taken in these studies aims to address this uncertainty by relying on a multi-model ensemble and providing percentiles. The results of the studies were published in 2020 for both the WLON-Ignace (Schardong et al. 2020) and the SON-South Bruce (Breach et al. 2020) areas.

In 2020, a new study was initiated to estimate the flood potentials and associated climate change impacts for the WLON-Ignace and the SON-South Bruce areas using the PMP, IDF and snowpack accumulation values estimated by Schardong et al. (2020) and Breach et al. (2020). A qualitative flood hazard assessment was first completed for the WLON-Ignace area, based on the IAEA Safety Standards guidelines entitled Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations (IAEA 2011). Flooding was then quantitatively assessed at the WLON-Ignace area for direct rainfall on-site and for upstream watershed flooding. A total of 14 scenarios were included in this preliminary flood hazard assessment. These scenarios are divided by period (current, mid-century, and end-of-century), climate change scenario (three PMP risk projections) and by type of flood (direct rainfall on-site and rainfall on upstream catchments). A hydraulic model was created, with the software HEC-RAS, to transform assumed extreme precipitation amounts into surface runoff depth in the WLON-Ignace area. The preliminary results are based on the current topography developed from the LiDAR data and do not consider grading or ditches. The results for the WLON-Ignace area were published in a technical report in 2021 (Rodriguez and Brown 2021). The study will continue in 2022 to estimate the flood potentials and associated climate change impacts for the SON-South Bruce area.

6.4.2.4 Site-Specific Properties for Safety Assessment

Pre-closure safety assessment in Sections 6.4.2.1 and 6.4.2.2 employs an environmental transfer model to calculate potential dose to the public from the airborne and aqueous releases from a nuclear facility under normal and accident conditions. CSA provides guidelines for the model calculations (CSA 2003, 2008 and 2014). CSA (2014) also provides regional default values for some parameters for southern Ontario, western Ontario, eastern Ontario, Quebec and Maritimes. However, there are no default values provided for aqueous dilution factors, and site specific data will be needed to determine these factors.

Depending on the site location, additional site-specific data may be needed and integrated with regional or other relevant generic data. These site-specific data will be acquired as parts of baseline monitoring program, e.g., installation of a meteorology tower in the WLON-Ignace area.

6.4.2.5 Behaviour of Used Fuel / Packages under Normal and Accident Conditions

A key aspect of the pre-closure safety assessment is the behaviour of the used fuel and packages under normal and accident conditions. CANDU fuel is a solid waste form, non-volatile and contained within Zircaloy sheathing. However, some used fuels may be damaged during transport to the DGR, or during handling within the UFPP. And all used fuels have small amount of surface contamination. These could result in some release of particulate, gases, or volatile elements from the used fuel. These releases would be handled within the surface facilities as part of the design basis (e.g., particulates captured on a High Efficiency Particulate Air (HEPA) filter system).

From a pre-closure safety assessment perspective, uncertainties in fuel integrity will be handled by conservative assumptions. Normal operations and accident assessments are discussed in Section 6.4.2.1 and 6.4.2.2 respectively. Of interest from a pre-closure safety assessment perspective are cases where the fuel is not yet sealed in a container, or the container itself is not fully closed. The NWMO are looking for opportunities to learn from others' used fuel handling experience such as participation in the NEA Expert Group on Operational Safety and data available in literature (for example, from U.S. Idaho National Laboratory (INL) 2005). Used fuel handling experiences at Canadian Nuclear Laboratories and at Ontario Power Generation's Dry Storage facilities will also be sought.

In order to estimate the radiological release source terms during a potential accident, the preliminary assessment as discussed in Section 6.4.2.2 follows the U.S. Department of Energy (DOE)'s five factor formula - material at risk, damage ratio, airborne release fraction, respirable fraction, and leakpath factor. The assigned values for the five factors in this study are based mostly on the U.S. DOE Handbook (U.S. DOE 1994) and the subsequent U.S. DOE standard (U.S. DOE 2007), as well as values used in the Yucca Mountain assessment (U.S. DOE 2009).

For preliminary normal operation assessment, as discussed in Section 6.4.2.1, radionuclide release from intact fuel bundles and fuel bundles with an intentionally defected fuel element are based on experimental data (Chen et al. 1986, 1989). A range of radionuclide release rates are reported in literature, and the highest measured release rates are conservatively used for the reference case. The fuel bundle failure rates during transportation and handling are considered to be low, as the fuel processing facilities in the UFPP will be designed to minimize the impact on the used fuel. Conservative assumptions are made to bound the uncertainty in the fuel bundle failure rates. These source term values are considered overall conservative, taking into account in part differences in used fuel characteristics, container and handling requirements (e.g., the lower burnup of CANDU bundles).

The NWMO will continue to monitor the literature and international practices, and experience in Canadian fuel handling to support these values.

6.4.3 Post-closure Safety

6.4.3.1 Post-closure Safety Assessment Methods

The purpose of a post-closure safety assessment is to determine the potential effects of the repository on the health and safety of persons and the environment during the post-closure timeframe.

The ability of the repository to safely contain and isolate used nuclear fuel is achieved by multiple barriers, these being the ceramic used fuel pellet, the fuel sheath, the robust long-lived container, a series of clay-based seals and backfill material, and the site-specific geology.

Preliminary work towards site-specific assessments of post-closure safety included:

- Using early results from literature surveys of measured rock permeabilities at varying depths for several sites across the Canadian Shield (Snowdon et al. 2021) to estimate general relationships between depth and rock permeability in the WLON-Ignace area;
- Adapting the 3D geological model of Southern Ontario by Carter et al. (2021b) to calculate groundwater flow and transport in the SON-South Bruce area;
- Developing complementary methods for calculating hypothetical transport of imagined contaminant transport within the rock neighbouring the repository vault; and
- Construction of groundwater flow and transport models, building on the approaches developed in previous case studies (e.g., Kremer et al. 2019).

Further effort was given to exploring additional metrics for assessing site suitability, including multiple types of water-supply wells, a broad set of lifestyles, and an expanded series of imagined repository failures.

Post-closure assessment methodology was based on guidance from the Canadian Nuclear Safety Commission (CNSC 2021).

6.4.3.1.1 Integrated System Model

In late 2018, the NWMO initiated development of a new system modelling tool known as the Integrated System Model (ISM). The ISM consists of a connected series of models developed in commercially available codes each representing a specific portion of the repository system. The ISM-NF model was developed using COMSOL and contains the waste form, containers, engineered barrier system, and excavation damaged zone surrounding the placement room. It assumes the failure of some containers, degradation of the used fuel by water, and transport of radionuclides and stable isotopes from the fuel, through the engineered barrier system and into the geosphere. The ISM-GEO model developed using HGS describes the movement of species from the repository via the groundwater through the rock mass and fractures, to the surface environment. The ISM-BIO model developed using AMBER determines the concentration of species in environmental media (e.g., surface water, groundwater, sediments, soils, air) and estimates the consequent radiological dose to a critical group living near the repository.

The initial versions (v1.0 and v1.0.1) of ISM were released in 2020. The theory of the component models is described in Gobien and Medri (2019). In 2021, ISM v1.1, is was released and included two versions of geosphere and biosphere models each representative the WLON-Ignace and the SON-South Bruce area. Other model improvements included addition of an improved solubility-limited release model in ISM-NF and consideration of number of additional lifestyles in the ISM-BIO model. An updated version of the ISM theory manual is expected to be published in 2022.

In 2021, the development of a data processing and linking tool known as paLINK was also completed. This tool will manage data preprocessing, stochastic data sampling, model linking, and postprocessing of ISM data and models. Figure 6-2 shows the structure of the combined paLINK-ISM configuration.

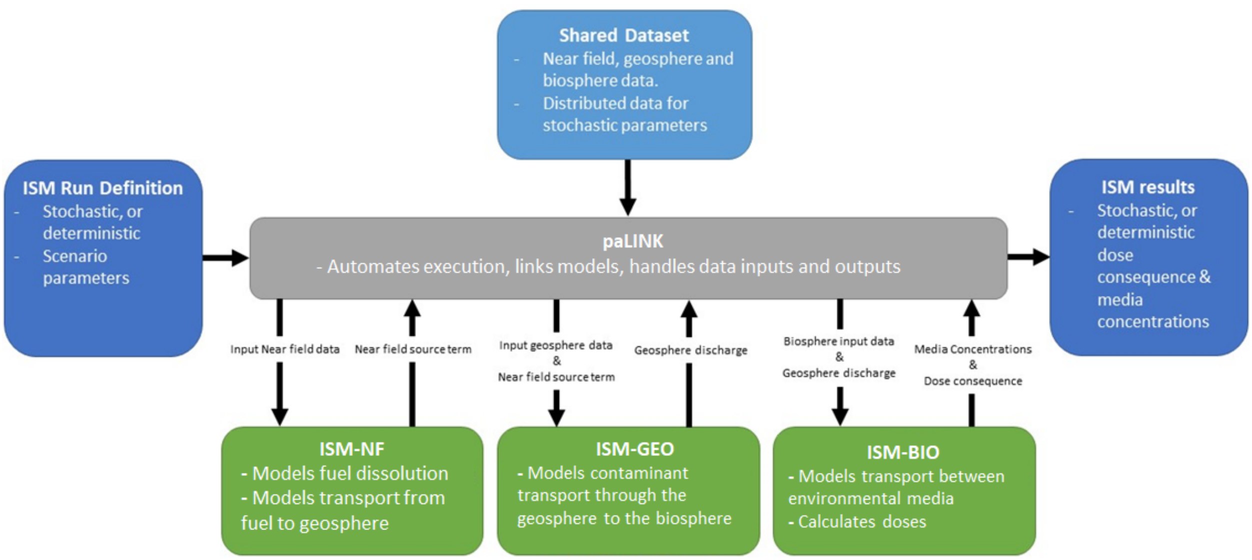


Figure 6-2: paLINK-ISM Configuration

The NWMO continues to develop and test the ISM in a manner consistent with NWMO technical computing software procedures, and with the CSA Standard N286.7-16 (CSA 2016). The next iteration of the ISM model, ISM v1.2, is planned to be released in 2022 and will increase the site-specificity of the geosphere and biosphere models as well as a number of other minor changes. For example, changing the suite of radionuclides and stable species included in the models to reflect the results of the 2021 screening analysis (see Section 6.4.1).

Validation of the ISM is an ongoing task, with further validation of specific process models or overall system-level comparisons performed when suitable opportunities arise (for example Decovalex Task F – see Section 4.3.3.2).

6.4.3.2 Acceptance Criteria

Acceptance criteria for radiological and non-radiological contaminants applicable to post-closure safety assessments are used to judge the acceptability of analysis results for the protection of humans and the environment. These proposed criteria have not been formally approved for use in a used fuel repository licence application.

Proposed acceptance criteria for the radiological protection of persons, expressed as an annual dose rate, are based on the recommendations of the ICRP (2007) and IAEA (2006) and aligned with the reference risk value of ICRP (2013), Health Canada (2010), and IAEA (2006).

There are presently no internationally agreed-upon environmental benchmarks of dose rate criteria against which to assess radiological effects to non-human biota. In the most recent post-closure safety assessment (NWMO 2018), the NWMO used a two-tiered criteria system, which includes proposed criteria from ERICA (Garnier-Laplace et al. 2006), PROTECT (Andersson et al. 2008), and the ICRP’s Derived Consideration Reference Levels (ICRP 2008). This approach is consistent with the approach proposed by BIOPROTA, an international forum that seeks to address key uncertainties in long-term assessments of contaminant releases into the environment arising from radioactive waste disposal (see Section 6.3.2).

Proposed acceptance criteria for the protection of persons and the environment from non-radiological contaminants were originally documented in Medri (2015), which presents criteria that span all environmental media (i.e., surface water, groundwater, soil, sediment and air) for a broad list of elements of relevance in a used fuel repository. In 2019, criteria for element-media combinations that were missing from Medri (2015) were developed using a comprehensive literature search, and through aquatic and terrestrial toxicity tests for rhodium and ruthenium (Fernandes et al. 2019). In 2021, an update to Medri (2015) was published (Medri 2021), taking into account Fernandes et al. (2019), updates to referenced guidelines and publications, and refined to the 17 elements identified as potentially important for post-closure safety assessment according to the Fuel Radiotoxicity and Screening Analysis (Gobien et al. 2021). The proposed acceptance criteria are based on the guidance of CNSC (2021). They are based on Canadian federal and Ontario provincial guidelines and publications, supplemented as required by interprovincially and internationally developed guidelines.

6.5 MONITORING

6.5.1 Knowledge Management

The NEA established in 2019 the Working Party on Information, Data and Knowledge Management (WP-IDKM) to further explore potential standardized approaches to manage information, as well to preserve the information in the long term for radioactive waste disposal and decommissioning. The work under this international collaboration builds on outcomes and learnings from recently completed NEA projects such as the Repository Metadata (RepMet) Management, and the Preservation of Records, Knowledge and Memory (RK&M) across Generations projects.

The NEA Repository Metadata (RepMet) Management project was a four-year initiative aimed 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 focused on the period before repository closure. The NWMO participated in this program since its start. An overview of the project, including deliverables produced since 2014, was presented in NEA (2018).

The NEA initiative on the Preservation of Records, Knowledge and Memory (RK&M) across Generations was a multi-year initiative looking to minimise the risk of losing records, knowledge and memory, with a focus on the period of time after repository closure. The NWMO participated in this program since its start. Three reports of the RK&M initiative were published in 2019, including the report describing the Key Information File concept for a repository (NEA 2019a), the report describing the Set of Essential Records concept for a repository (NEA 2019b), and the RK&M final report (NEA 2019c).

In 2021, NWMO continued monitoring the international collaborations and research on knowledge management and long-term preservation of knowledge and records.

7 SITE ASSESSMENT

In 2021, we continued to assess the potential suitability of siting areas within two regions in Ontario: the WLON-Ignace area in northwestern Ontario, and the SON-South Bruce area in southern Ontario. The status of the geological and environmental studies underway in these regions is described below.

7.1 WABIGOON LAKE OJIBWAY NATION (WLON)-IGNACE AREA

7.1.1 Geological Investigation

By the end of 2021, the Geoscience Site Assessment team and their contractors completed the drilling of 6 kilometre-long boreholes in the crystalline rock of the Revell Batholith west of Ignace, Ontario. Fieldwork continued in 2021, with COVID-19 protocols in place, and following government guidelines. Downhole testing of the sixth borehole is planned to continue into Spring 2022.

Figure 7-1: Drilling and testing of Borehole 5 in the WLON-Ignace area.

In 2021, installation of the full 9-station microseismic monitoring network in the region was completed, and monitoring is ongoing

Geological mapping at the WLON-Ignace area, and installation of a shallow groundwater monitoring network was also completed in 2021

7.1.2 Environmental Assessment

Despite COVID 19 restrictions and NWMOs commitment to keeping siting communities safe the NWMO in partnership with environmental consultants and community partners completed a great deal of environmental work in the Northwest Region in 2021. Some of this work included: meteorological observation station installation, year 1 environmental media baseline monitoring work, Tier 1 environmental biodiversity work, bat research, environmental monitoring/compliance for other work programs completed in the Northwest and ongoing engagement related to the environmental program. Details of the work completed for in 2021 are described below.

7.1.2.1 Metrological Observation Station

To support baseline environmental monitoring in the Northwest siting region the NWMO contracted Campbell Scientific to design, install and commission a meteorological observation station (Figure 7-2) at the Borehole 1 location within the area of interest (AOI). The station was installed mid-August, collects environmental conditions every 15 minutes and reports this information every hour to a cloud-based data management system. Parameters measured by the station include air temperature, total precipitation, snow depth, wind speed and direction, relative humidity, atmospheric pressure, soil temperature and moisture, and solar radiation.

Figure 7-2: Meteorological Observation Station Installed at the Borehole 1 Site

7.1.2.2 Baseline Media Sampling and Biodiversity

Another key piece of work completed in the Northwest for 2021 included the commencement of baseline monitoring for both environmental media and biodiversity. To complete this work the NWMO contracted KGS Group as the environmental baseline data collection consultant. Baseline media work completed in 2021 included: surface water quality monitoring, hydrology, and soil quality monitoring. Surface water quality monitoring was completed by North South Consulting, a subcontractor of KGS. A summer and fall campaign were completed accounting for a total of 39 sites visited and 140 samples collected. Hydrology monitoring was completed in house by KGS group and included bathymetry and lake level monitoring at 11 lake and pond sites and flow monitoring at 6 stream and river sites. Soil quality monitoring was completed by Ecostem, another subconsultant of KGS group, and consisted of samples being collected at a total of 15 sites.

Baseline biodiversity work completed in 2021 included: aquatic eDNA sampling, terrestrial ecosystem/habitat suitability mapping and aquatic habitat mapping. aquatic eDNA sampling (Figure 7-3) was completed by North South Consulting in partnership with Wabigoon Lake Ojibway Nation community members. In addition, the NWMO developed a partnership with the University of Guelph to support training for data collection, completion of sample analysis and data interpretation. Through summer and fall sample campaigns field crews visited 153 collection sites and collected a total of 467 aquatic eDNA samples. Terrestrial ecosystem/habitat suitability mapping surveys were completed by KGS in conjunction with subconsultants, Ecostem and LGL Limited. Throughout the summer and fall months these crews mapped a total of 600 sites which account for approximately two thirds of the Tier 1 program. Aquatic habitat mapping was completed by North South Consulting and including the completion of surveys at a total of 287 sites (146 wetland, 13 pond, 32 lake and 86 stream/river sites).

Figure 7-3: Photo Showing Equipment Used to Collect Aquatic eDNA Samples

7.1.2.3 Bat Research in Partnership with the Toronto Zoo

The NWMO has partnered with the Toronto Zoo Native Bat Conservation Program in conducting research to close knowledge gaps in the ecology of Ontario's bat population. The goal of this work is to contribute to conservation efforts now and in the future, which starts with studies to better understand bat populations and trends. Work completed in the Northwest for 2021 included passive bat motoring at two sites within the AOI using acoustic monitoring devices as well as two evenings and nights spent evaluating potential bat habitat and actively monitoring for the presence of bats on site.

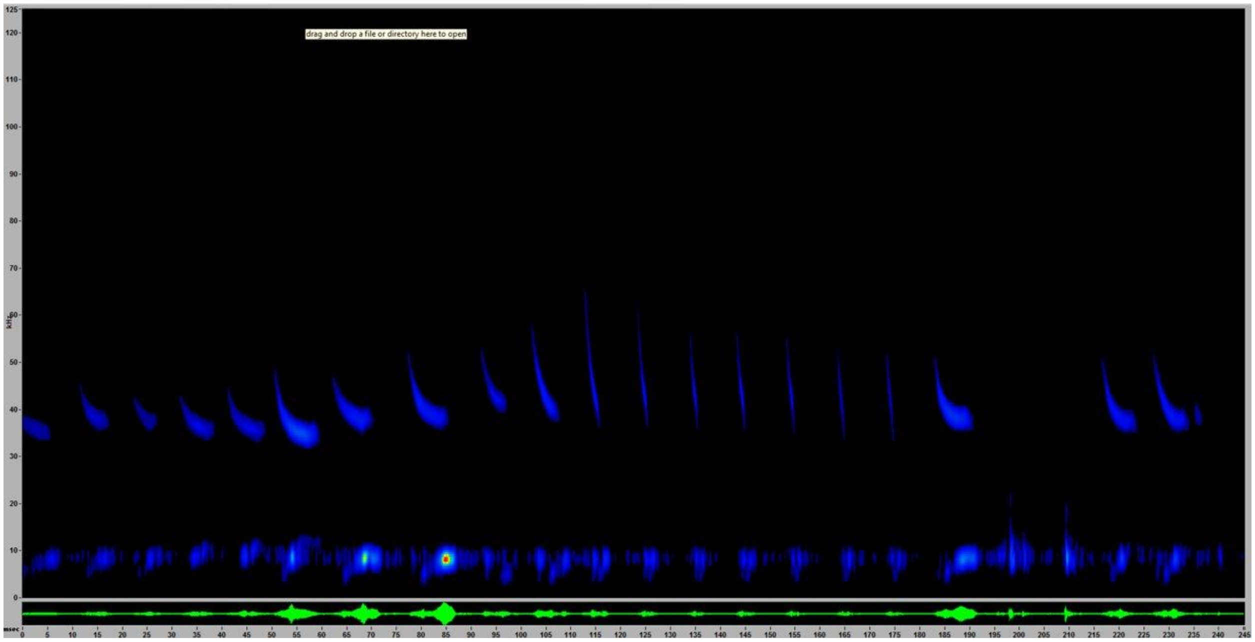


Figure 7-4: Photo Showing a Spectrogram of a Bat Call. The Software Visually Represents Species Specific Bat Sounds Not Heard by the Human Ear and Can be Used to Actively Monitor for the Presence of Bat Species

7.1.2.4 Compliance and Monitoring

The NWMO environmental team also provided environmental monitoring and compliance oversight to contractors completing work in the WLON-Ignace area throughout the year. Most of this work was overseen by the geoscience and project management groups and consisted of borehole drilling activities, trail clearing and seismic work. Environmental oversight for these work packages included ensuring adherence to the contractors HSE plans, completing spot checks and ensuring minor environmental impacts were mitigated appropriately.

7.1.2.5 Engagement

Engagement related to the environmental program is ongoing in the Northwest. In 2021 this included representation at community events such as open houses and providing information and updates to community groups such as the ICNLC and other interest groups.

7.1.2.6 Planned 2022 Work

Going forward into 2022 the environmental team aims to continue monitoring and compliance initiatives for work completed in the Northwest, continue working with community members as part of the baseline monitoring program and continue executing the Environmental Baseline Monitoring Program as designed. Baseline media sampling for 2022 will include continuing with water quality monitoring, soil quality monitoring and hydrology programs. Additional work will include tissue chemistry and atmospheric monitoring (air quality, noise, and light). Biodiversity baseline work for 2022 will include the completion of Tier 1 studies for aquatic eDNA, aquatic habitat mapping as well as terrestrial ecosystem/habitat suitability mapping. Additional biodiversity work may include Tier 2 studies including a winter aerial moose inventory. Lastly, bat research will be ongoing with plans to completed further active and passive monitoring in partnership with the Toronto Zoo Native Bat Conservation Program.

7.2 SAUGEEN OJIBWAY NATION (SON)-SOUTH BRUCE AREA

7.2.1 Geological Investigation

In 2021, NWMO's geoscience work at the potential repository site in this area continued. Site assessment activities in the SON-South Bruce area in 2021 included the drilling and testing of borehole 1 and initiating the drilling and testing of borehole 2. In addition, a 3D seismic survey was completed in the area in Fall 2021. Installation of a microseismic monitoring network in the region was completed, and installation of a shallow groundwater monitoring network began in 2021 and is planned to be completed in early 2022.

Figure 7-5: 3D Seismic Data Acquisition, November 2021

7.2.2 Environmental Assessment

Environmental field work in the SON-South Bruce area completed in 2021 included the surface water and hydrology components of the Environmental Media Baseline Program (EMBP), private drinking water sampling, and bat studies. Ongoing engagement related to the environment program, and environmental monitoring of site investigation studies also continued. Details of the work completed in 2021 are described below.

7.2.2.1 Surface Water Quality and Hydrology

The NWMO and Saugeen Valley Conservation Authority (SVCA) launched a joint program to further understand water resources in the SON-South Bruce and surrounding area.

As part of this program, the SVCA is undertaking the surface water quality component of the EMBP in the SON-South Bruce area. The SVCA completed the fall 2021 surface water quality sampling campaign throughout the Saugeen watershed (Figure 7-6). This work will continue to be executed by the SVCA in 2022-2023, as designed in the Environmental Baseline Monitoring Program.

The SVCA also initiated the Hydrology component of the EMBP, including staff gauge installations and monthly water level measurements; two flow station installations along the Teeswater River; and bathymetry surveys of three lakes within the Saugeen watershed.

One meteorological observation station (design described in Section 7.1.2.1) was installed within the Area of Interest (AOI) in the SON-South Bruce area. The station records hourly data and is monitored and maintained by the SVCA.

Figure 7-6: SVCA Staff Monitoring Water Levels and Sampling Surface Water at a Wetland Site, November 2021

7.2.2.2 Private Water Well Sampling

As part of the NWMO's environmental baseline monitoring program developed with the community, Tulloch Environmental was contracted to complete private water well sampling in the area near the potential repository site in the SON-South Bruce area (Figure 7-7). The program was voluntary and provided landowners an opportunity to find out their existing drinking water quality. A total of 10 wells were sampled in Spring 2021, and landowners were provided the results in the summer of 2021.

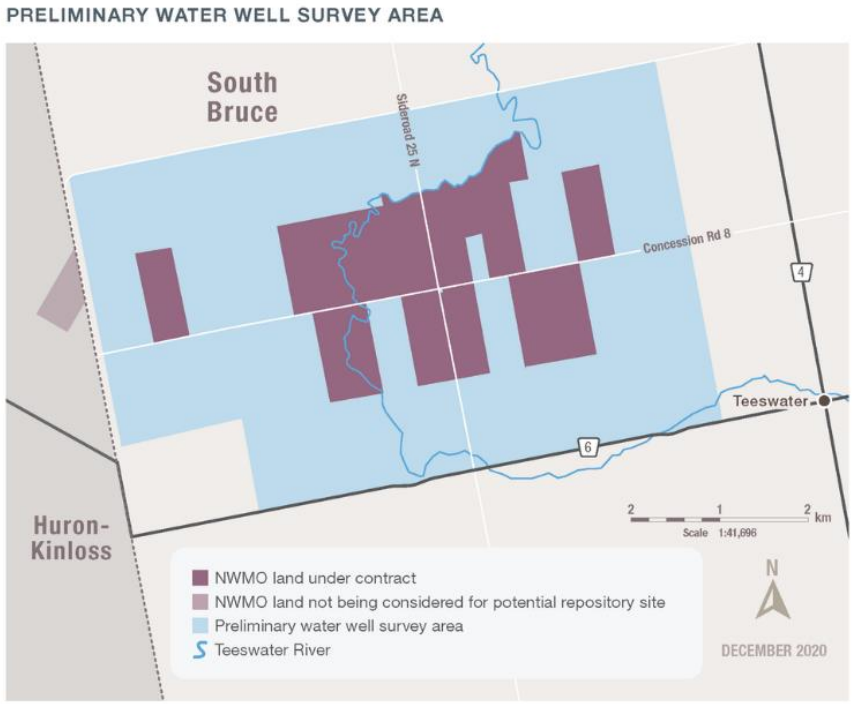


Figure 7-7: Map of the Area Where the 2021 Water Well Sampling Program was Offered to Property Owners near NWMO Acquired Lands

7.2.2.3 Bat Research in Partnership with the Toronto Zoo

Field studies of local bat populations and their trends near the SON-South Bruce area were completed as part of The Toronto Zoo's Native Bat Conservation Program in partnership with the Nuclear Waste Management Organization (NWMO). This partnership includes developing and testing innovative monitoring techniques that can improve how bats are studied. Data was collected using acoustic bat monitors and researchers also initiated temporary capture and release, as well as radio telemetry studies.

As part of this partnership, the Toronto Zoo also implemented a successful community science pilot program in the SON-South Bruce area, where members of the public collaborated with professional scientists to collect and analyze data related to local bat populations. A total of 15 volunteers were engaged, and 18 monitoring sites were sampled over 116 nights

7.2.2.4 Compliance and Monitoring

The NWMO Environmental Assessment (EA) group also provided environmental monitoring and compliance oversight to contractors completing work in/near the SON-South Bruce area throughout the year. Most of this work was overseen by the geoscience and project management groups and consisted of borehole drilling activities, 3-D seismic work and micro seismic station installation as well as additional site reconnaissance. Environmental oversight for these work packages included, completing spot checks, soil, and surface water sample collection on borehole sites, and ensuring minor environmental impacts were mitigated appropriately.

7.2.2.5 Engagement

The NWMO EA group continues to engage the communities in and around the SON-South Bruce area about the Environmental Baseline Monitoring Program. This includes but is not limited to updates to the South Bruce community liaison committee (CLC), indigenous groups, community groups, and local municipal leaders. Additionally, the NWMO continues to engage with local property owners who allow property access for environmental baseline studies, and local residents who enquire about our baseline monitoring work throughout the year.

7.2.2.6 Planned 2022 Work

Going forward into 2022 the environmental team aims to continue monitoring and executing compliance initiatives for work completed in the SON-South Bruce area, engage with community members as part of the baseline monitoring program, and continue executing the Environmental Baseline Sampling Program as designed. Baseline media sampling for 2022 is planned to include surface water sampling, hydrology, soil sampling, and the launch of the atmospheric monitoring and tissues programs. Biodiversity work for 2022 is planned to include eDNA, aquatic habitat mapping and terrestrial ecosystem mapping programs, which are heavily dependent on private land access. Lastly, bat research will be ongoing with plans to complete further active and passive monitoring in partnership with the Toronto Zoo Native Bat Conservation Program.

REFERENCES

Ackerley, N., V. Peci, J. Adams and S. Halchuk. 2021. Seismic Activity in the Northern Ontario Portion of the Canadian Shield: Annual Progress Report for the Period January 1 – December 31, 2019. Nuclear Waste Management Organization Technical Report, NWMO-TR-2021-10. Toronto, Canada.

AECL. 1994. Environmental Impact Statement on the concept for disposal of Canada's nuclear fuel waste. Atomic Energy of Canada Limited Report AECL-10711, COG-93-1. Chalk River, Canada.

Al, T., I. Clark, L. Kennell, M. Jensen and K. Raven. 2015. Geochemical evolution and residence time of porewater in low-permeability rock of the Michigan Basin, Southwest Ontario. Chemical Geology, 404, 1-17.

Al-Aasm I., R. Crowe and M. Tortola. 2021. Dolomitization of Paleozoic Successions, Huron Domain of Southern Ontario, Canada: Fluid Flow and Dolomite Evolution Water 13 (17), 2449.

Al-Aasm, I.S. and R. Crowe. 2018. Fluid compartmentalization and dolomitization in the Cambrian and Ordovician successions of the Huron Domain, Michigan Basin. Marine and Petroleum Geology, 92, 160-178.

Alcorn, C.D., J.S. Cox, L. Applegarth and P. Tremaine. 2019. Investigation of uranyl sulfate complexation under hydrothermal conditions by quantitative Raman spectroscopy and density functional theory, Journal of Physical Chemistry B 123, 7385-7409.

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

Andersson, P., K. Beaugelin-Seiller, N.A. Beresford, D. Copplestone, C. Della Vedova, J. Garnier-Laplace, B. J. Howard, P. Howe, D.H. Oughton, C. Wells, P. Whitehouse. 2008. Deliverable 5: Numerical benchmarks for protecting biota from radiation in the environment: proposed levels, underlying reasoning and recommendations. PROTECT. Stockholm, Sweden.

Aquanty Inc. 2018. HydroGeoSphere User Manual, Aquanty Inc., Waterloo, Canada.

Bailey Geological Services Ltd. and Cochrane, R.O. 1984a. Evaluation of the conventional and potential oil and gas reserves of the Cambrian of Ontario. Ontario Geological Survey, Open File Report 5499. Ontario, Canada.

Bailey Geological Services Ltd. and Cochrane, R.O. 1984b. Evaluation of the conventional and potential oil and gas reserves of the Ordovician of Ontario. Ontario Geological Survey, Open File Report 5498. Ontario, Canada.

Bastola, S., L. Fava and M. Cai. 2015. Validation of MoFrac 2.0 using the Äspö dataset. Nuclear Waste Management Organization Technical Report NWMO-TR-2015-25. Toronto, Canada.

Beaver, R.C., K. Engel, W.J. Binns and J.D. Neufeld. 2021. Microbiology of barrier component analogues of a deep geological repository. Can. J. Microbiol. (99) 999, 1-18.

Birkholzer, J.T., C.F. Tsang, A.E Bond, J.A. Hudson, L. Jing and O. Stephansson. 2019. 25 years of DECOVALEX - Scientific advances and lessons learned from an international research collaboration in coupled subsurface processes. International Journal of Rock Mechanics and Mining Sciences; 122, 103995.

Blain-Coallier A. 2020. Surface permeability mapping of Stanstead and Lac du Bonnet granite, MEng Thesis, McGill University.

Breach, P., J. Kelly and S. Capstick. 2020. Climate Change Impacts on Climate Variables for a Deep Geological Repository (South Bruce Study Area). Nuclear Waste Management Organization Technical Report NWMO-TR-2020-09. Toronto, Canada.

Briggs, S., C. Lilja and F. King. 2020a. Probabilistic model for pitting of copper canisters. Materials and Corrosion, 72(1-2). doi.org/10.1002/maco.202011784

Briggs, S., C. Lilja and F. King. 2020b. Probabilistic model for pitting of copper canisters under aerobic, saturated conditions. Svensk Kärnbränslehantering AB. SKB TR-20-01. Forsmark, Sweden.

Brooks, G. 2021. Insights into the Connaught sequence of the Timiskaming varve series from Frederick House Lake, northeastern Ontario. Canadian Journal of Earth Sciences, 58(12).

Carter, T.R., L.D. Fortner, H.A.J. Russell, M.E. Skuce, F.J. Longstaffe and S. Sun. 2021a. A Hydrostratigraphic Framework for the Paleozoic Bedrock of Southern Ontario. Geoscience Canada, 48, 23- 58.

Carter, T.R., C.E Logan, J.K. Clark, H.A.J Russell, F.R. Brunton, A. Cachunjua, M. D'Arienzo, C. Freckelton, H. Rzyszczak, S. Sun, and K.H. Yeung. 2021b. A three-dimensional geological model of the Paleozoic bedrock of southern Ontario—version 2; Geological Survey of Canada, Open File 8795, 1. doi.org/10.4095/328297.

Chen, Z., P. Hannigan, T. Carter, X. Liu, R. Crowe and M. Obermajer. 2021. A petroleum resource assessment of the Huron Domain. Nuclear Waste Management Organization Technical Report NWMO-TR-2019-20. Toronto, Canada.

Chen, J.D., A.H. Kerr, E.A. Hildebrandt, E.L. Bialas, H.G. Delany, K.M. Wasywich, and C.R. Frost. 1989. Radiochemical Analysis of CANDU Used Fuel Stored in Concrete Canisters in Moist Air at 150°C. Proceedings Second International Conference on CANDU Fuel. pp. 337 – 351. Pembroke, Canada, October 1-5, 1989 (Also available at https://inis.iaea.org).

Chen, J.D., P.A. Seeley, R. Taylor, D.C. Hartrick, N.L. Pshhyshlak, K.H. Wasywich, A. Rochon and K.I. Burns. 1986. Characterization of Corrosion Deposits and the Assessment of Fission Products Released from Used CANDU Fuel. Proceedings 2nd International Conference on Radioactive Waste Management. Winnipeg, Canada, 7-11 September 1986. Canadian Nuclear Society, Canada.

Clark, I.D., T. Al, M. Jensen, L. Kennell, M. Mazurek, R. Mohapatra and K. Raven. 2013. Paleozoic-aged brine and authigenic helium preserved in an Ordovician shale aquiclude. Geology, 41, 9, 951-954.

CNSC. 2021. Safety Case for the Disposal of Radioactive Waste, Version 2. Canadian Nuclear Safety Commission Regulatory Document CNSC REGDOC-2.11.1 Volume III, Version 2. Ottawa, Canada.

Colàs, E., A. Valls, D. García and L. Duro. 2021. Radionuclide Solubility Calculation (Phase 1). Nuclear Waste Management Organization Technical Report NWMO-TR-2021-02. Toronto, Canada.

CSA. 2003. Guidelines for Calculating Radiation Doses to the Public from a Release of Airborne Radioactive Material under Hypothetical Accident Conditions in Nuclear Reactors. Canadian Standards Association CSA N288.2-M91. Toronto, Canada.

CSA. 2008. Guidelines for Calculating Derived Release Limits for Radioactive Material in Airborne and Liquid Effluents for Normal Operation of Nuclear Facilities. Canadian Standards Association CSA Guideline N288.1-08. Toronto, Canada.

CSA. 2014. Guidelines for Calculating the Radiological Consequences to the Public of a Release of Airborne Radioactive Material for Nuclear Reactor Accidents. Canadian Standards Association CSA N288.1-14. Toronto, Canada.

Damiani H. L., G. Kosakowski, A. Vinsot and S.V. Churakov. 2022. Hydrogen gas transfer between a borehole and claystone: experiment and geochemical model. Submitted to Environmental Geotechnics. doi:10.1680/jenge.21.00061.

Darcel C., P. Davy, R. Le Goc and D. Mas Ivars. 2018. Rock mass effective properties from a DFN approach. Proceedings of 2nd International Discrete Fracture Network Engineering Conference, Seattle, USA, June 20-22, 2018. American Rock Mechanics Association.

Davy, P., R. Le Goc, C. Darcel, J.O. Selroos, D. Mas Ivars. 2021. Permecability: Factoring Stress Dependency Into The Permeability Of Fractured Rocks. American Geophysical Union Fall Meeting 2021, Dec 2021, New Orleans, USA.

Davy P., C. Darcel, R. Le Goc, and D. Mas Ivars. 2018. Elastic properties of fractured rock masses with frictional properties and power - law fracture size distributions. Journal of Geophysical Research: Solid Earth. 123, 6521-6539. doi:10.1029/2017JB015329

Davy P., A. Hansen, E. Bonnet, S-Z. Zhang. 1995. Localization and fault growth in layered brittle-ductile systems: Implications for deformations of the continental lithosphere. Journal of Geophysical Research: Solid Earth. Volume 100, issue B4, p. 6281-6294.

Diederichs, M., and J. Day. 2021. An illustrative study on the potential sensitivity of predicted long-term EDZ development to, layered and nodular sedimentary structure. Rock Mechanics and Rock Engineering. doi:10.1007/s00603-021-02602-z.

Esmaieli K., J. Hadjigeorgiou and M. Grenon. 2010. Estimating geometrical and mechanical REV based on synthetic rock mass models at Brunswick Mine. International Journal of Rock Mechanics and Mining Sciences. 47(6), 915-926

Fernandes, S., K. Woolhouse and N. Thackeray. 2019. Supplementary Non-Radiological Interim Acceptance Criteria for the Protection of Persons and the Environment. Nuclear Waste Management Organization Technical Report NWMO-TR-2017-05. Toronto, Canada.

Fischer, C. and M.S. Diederichs. 2021a. The use of explicit numerical models for the prediction of residual rockmass behaviour around a circular tunnel. GEONiagara – CGS conference 2021. Niagara Falls, Canada.

Fischer, C. and M.S. Diederichs. 2021b. Comparison between GSI-based implicit and explicit structure models. In The Evolution of Geotech-25 Years of Innovation p. 527-533. CRC Press.

Gao, K. and J.P. Harrison. 2016. Mean and dispersion of stress tensors using Euclidean and Riemannian approaches. International Journal of Rock Mechanics and Mining Sciences. 85, 165-173.

Gao, K. and J. P. Harrison. 2018a. Multivariate distribution model for stress variability characterisation. International Journal of Rock Mechanics and Mining Sciences. 102, 144-154.

Gao, K. and J.P. Harrison. 2018b. Scalar-valued measures of stress dispersion. International Journal of Rock Mechanics and Mining Sciences. 106, 234-242.

Garnier-Laplace, J., R. Gilbin, A. Agüero, F Alonzo, M. Björk, Ph. Ciffroy, D. Copplestone, M. Gilek, T. Hertel-Aas, A. Jaworska, C-M. Larsson, D. Oughton and I. Zinger. 2006. Deliverable 5: Derivation of Predicted-No-Effect-Dose-Rate values for ecosystems (and their sub-organisational levels) exposure to radioactive substances. ERICA (Contract Number: FI6R-CT-2004-508847). Brussels, Belgium.

Gobien, M. and C. Medri. 2019. ISM v1.0 Theory Manual. Nuclear Waste Management Organization Technical Report NWMO-TR-2019-06. Toronto, Canada.

Gobien, M. and M. Ion. 2021. Nuclear Waste Fuel Projections in Canada – 2021 Update. Nuclear Waste Management Organization Technical Report NWMO-TR-2021-17. Toronto, Canada.

Gobien, M., K. Liberda, and C. Medri. 2021. Fuel Radiotoxicity and Screening Analysis. Nuclear Waste Management Organization Technical Report NWMO-TR-2021-16 R001. Toronto, Canada.

Goguen, J., A. Walker, J. Riddoch, S. Nagasaki. 2021. Sorption of Pd on illite, MX-80 and shale in Na-Ca-Cl solutions, Nuclear Engineering and Technology 53 (3), 894-900. doi: doi.org/10.1016/j.net.2020.09.001

Golder Associates Ltd. 2005. Hydrocarbon Resource Assessment of the Trenton-Black River Hydrothermal Dolomite Play in Ontario. Ontario Oil, Gas and Salt Resources Library. London, Canada.

Grenthe, I., X. Gaona, A.V. Plyasunov, L. Rao, W.H. Runde, B. Grambow, R.J.M. Konings, A.L. Smith and E.E. Moore. 2020. Second Update on the Chemical Thermodynamics of

Uranium, Neptunium, Plutonium, Americium and Technetium. Vol 14. OECD Nuclear Energy Agency Data Bank, Eds., OECD Publications, Paris, France.

Grenthe, I., J. Fuger, R.J.M. Konings, R.J. Lemire, A.B. Muller, C. Nguyen-Trung and H. Wanner. 1992. Chemical Thermodynamics of Uranium. Elsevier Science Publishers, New York, United States.

Hall, D.S., M. Behazin, W.J. Binns and P.G. Keech. 2021. An evaluation of corrosion processes affecting copper-coated nuclear waste containers in a deep geological repository. Progress in Materials Science, 118, 100766.

Harper, J., T. Meierbachtol, N. Humphrey, J. Saito and A. Stansberry. 2021. Generation and Fate of Basal Meltwater During Winter, Western Greenland Ice Sheet. The Cryosphere, 15, 5409–5421. doi:10.5194/tc-15-5409-2021

Harthong, B., L. Scholtès, F-V. Donzé. 2012. Strength characterization of rock masses, using a coupled DEM–DFN model. Geophysical Journal International. 191(2), 467-480. doi:10.1111/j.1365-246X.2012.05642.x

Health Canada. 2010. Part IV Guidance on Human Health Detailed Quantitative Radiological Risk Assessment. Ottawa, Canada.

Heckman, K. and J. Edward. 2020. Radionuclide Inventory for Reference CANDU Fuel Bundles. Nuclear Waste Management Organization Technical Report NWMO-TR-2020-05. Toronto, Canada.

Hegger, S., N. Vlacholpoulos and M. Diederichs. 2021a. A New Apparatus for Installing Distributed Optical Sensors onto Uniaxial Compression Test Specimens to Measure Full-Field Strain Responses. Geotechnical Testing Journal 45(1). doi:10.1520/GTJ20210021

Hegger, S., N. Vlachopoulos, T. Poles, and M. Diederichs. 2021b. Measuring the full-field strain response of uniaxial compression test specimens using distributed fiber optic sensing. Rock Mechanics and Rock Engineering. doi:10.1007/s00603-021-02643-4

Innocente, J., M. Diederichs, C. Paraskevopoulou. 2021. Long-term strength; time-dependency; time-dependent cracking; static load testing; Creep; time-to-failure. International Journal of Rock Mechanics and Mining Science. V147. 13p. doi:10.1016/j.ijrmms.2021.104900

IAEA. 2006. Safety Requirements: Geological Disposal of Radioactive Waste. International Atomic Energy Agency Safety Requirements WS-R-4. Vienna, Austria.

IAEA. 2011. Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. SSG-18, IAEA, Vienna, Austria.

ICRP. 2007. The 2007 Recommendations of the International Commission on Radiological Protection. International Commission on Radiological Protection Publication 103, Annals of the ICRP (W2-4). Vienna, Austria.

ICRP. 2008. Environmental Protection: The Concept and Use of Reference Animals and Plants. ICRP Publication 108. Vienna, Austria.

ICRP. 2013. Radiological Protection in Geological Disposal of Long-lived Solid Radioactive Waste. International Commission on Radiological Protection Publication 122, Annals of the ICRP 42(3). Vienna, Austria.

INL. 2005. Damaged Spent Fuel at U.S. DOE Facilities, Experience and Lessons Learned. Idaho National Laboratory Report INL/EXT-05-00760. Idaho, USA.

ITASCA. 2015. Long-Term Stability Analysis of APM Conceptual Design in Sedimentary and Crystalline Rock Settings. Itasca Consulting Group, Inc. report for NWMO. Nuclear Waste Management Organization Technical Report NWMO-TR-2015-27. Toronto, Canada.

Jacobsson, L., D. Mas Ivars, H.A. Kasani, F. Johansson and T. Lam. 2021. Experimental program on mechanical properties of large rock fractures, EUROCK 2021, Torino, Italy, 20-25 September 2021, IOP Conf. Ser.: Earth Environ. Sci. 833 012015. doi.10.1088/1755-1315/833/1/012015

Jaquenoud, M., T.E. William, T. Grundl, T. Gimmi, A. Jakob, S. Schefer, V. Cloet, P. De Canniere, L. R. Van Loon and O.X. Leupin. 2021. In-situ X-ray fluorescence to investigate iodide diffusion in opalinus clay: Demonstration of a novel experimental approach, Chemosphere 269, 128674

Javaid, M.A., J.P. Harrison, M.I. Diego and H. Kasani. 2021a. Assessing heterogeneity of in situ stress for the design of nuclear waste repositories. GeoNiagara 2021: 74th Canadian Geotechnical Conference & 14th Joint CGS/IAH-CNC Groundwater Conference, Niagara, Canada.

Javaid, M.A. and J.P. Harrison. 2021b. Heterogeneity of in situ stress: A Review. EUROCK 2021: ISRM Symposium on Mechanics and Rock Engineering from Theory to Practice, Torino, Italy.

Junkin, W., L. Fava, M. Cai, E. Ben Awuah. 2020. Using DFN models to improve ground control through wedge identification and hazard mapping. Extended abstract, geoconvention, May 11-13, Calgary, Canada.

Junkin, W., E. Ben-Awuah and L. Fava. 2019a. DFN variability analysis through voxelization. Proc. ARMA 2019, 53rd US Rock Mechanics/Geomechanics Symposium, New York, USA.

Junkin, W., E. Ben-Awuah and L. Fava. 2019b. Incorporating DFN analysis in rock engineering systems blast fragmentation models. Proc. ARMA 2019, 53rd US Rock Mechanics/Geomechanics Symposium, New York, USA.

Junkin, W., L. Fava, E. Ben-Awuah and R.M. Srivastava. 2018. Analysis of MoFrac-generated deterministic and stochastic Discrete Fracture Network models. Proc. DFNE 2018, 2nd International Discrete Fracture Network Engineering Conference, Seattle, USA.

Junkin W., D. Janeczek, S. Bastola, X. Wang, M. Cai, L. Fava, E. Sykes, R. Munier and R.M. Srivastava. 2017. Discrete Fracture Network generation for the Äspö TAS08 tunnel using MoFrac. Proc. ARMA 2017, 51st US Rock Mechanics/Geomechanics Symposium, San Francisco, USA.

Kanik, N.J., F.J. Longstaffe, A. Kuligiewicz and A. Derkowski. (*in press*). Systematics of smectite hydrogen-isotope composition: Structural hydrogen versus absorbed water. Submitted to Applied Clay Science.

King, F. 2021. Natural Analogues and Their Use in Supporting the Prediction of the Long-Term Corrosion Behaviour of Copper-Coated UFC. Nuclear Waste Management Organization Report Technical Report NWMO-TR-2021-19. Toronto, Canada.

Kremer, E.P., J.D. Avis, J. Chen, P.J. Gierszewski, M. Gobien, R. Guo and C. Medri. 2019. Postclosure Safety Assessment of a Canadian Used Fuel Repository. 4th Canadian Conference on Nuclear Waste Management, Decommissioning and Environmental Restoration. Ottawa, Canada.

Lampman, T. 2021. Update to Fuel Burnups and Power Ratings. Nuclear Waste Management Organization Technical Report NWMO-TR-2019-04. Toronto, Canada.

Larsson, J. 2021a. Experimental investigation of the system normal stiffness of a 5 MN direct shear test setup and the compensation of it in CNS direct shear tests, EUROCK 2021, Torino, Italy, 20-25 September 2021. IOP Conf. Ser.: Earth Environ. Sci. 833 012011. doi:10.1088/1755-1315/833/1/012011

Larsson, J. 2021b. Quality aspects in direct shear testing of rock joints, Licentiate thesis KTH Royal Institute of Technology, Stockholm, Sweden, TRITA-ABE-DLT, 2113.

Le Goc R., C. Darcel, P. Davy, M. Pierce and M.A. Brossault. 2014. Effective elastic properties of 3D fractured systems. Proceedings of Discrete Fracture Network Engineering. Vancouver, Canada.

Le Goc R., P. Davy, and C. Darcel. 2015. Scaling effects on elastic properties of jointed rock mass. Proceedings of Eurock. Salzburg, Austria.

Lemire, R.J., D.A. Palmer, P. Taylor and H. Schlenz. 2020. Chemical Thermodynamics of Iron, Part 2, Vol 13b. OECD Nuclear Energy Agency Data Bank, Eds., OECD Publications. Paris, France.

Liberda, K. 2020. Preliminary Radon Assessment for a Used Fuel Deep Geological Repository. Nuclear Waste Management Organization Technical Report NWMO-TR-2019-09. Toronto, Canada.

Liebscher, A., I. Aaltonen, N. Diomidis, C. Lilja, S. Norris, H. Reijonen and L. Waffle. 2021. Michigan International Copper Analogue (MICA) project – recent advances [abstract]. In: safe ND: Interdisciplinary research symposium on the safety of nuclear disposal practices. November 10-12; Berlin, Germany. Saf. Nucl. Waste Disposal, 1, 129–130, 20.

Liljedahl, L. C., T. Meierbachtol, J. Harper, D. van As, J.O. Näslund, J.O. Selroos, J. Saito, S. Follin, T. Ruskeeniemi, A. Kontula and N. Humphrey. 2021. Rapid and sensitive response of Greenland's groundwater system to ice sheet change. Nature Geoscience. 14(10), pp.751-755. doi:10.1038/s41561-021-00813-1

Liu L., S. Giger, D. Martin, R. Chalaturnyk and N. Deisman. 2021. Stress and strain dependencies of shear modulus from pressuremeter tests in Opalinus Clay. *In:* The 6th International Conference on Geotechnical and Geophysical Site Characterization. Budapest, Hungary.

Liu, N., H. He, J.J Noël and D.W. Shoesmith. 2017a. The electrochemical study of Dy_2O_3 doped UO_2 in slightly alkaline sodium carbonate/bicarbonate and phosphate solutions, Electrochimica Acta 235, 654-663.

Liu, N., J. Kim, J. Lee, Y-S. Youn, J-G. Kim, J-Y. Kim, J.J Noël and D.W. Shoesmith. 2017b. Influence of Gd doping on the structure and electrochemical behavior of UO2, Electrochimica Acta 247, 496-504.

Liu, N., Z. Qin, J.J Noël and D.W. Shoesmith. 2017c. Modelling the radiolytic corrosion of a-doped UO_2 and spent nuclear fuel, Journal of Nuclear Materials 494, 87-94.

Liu, N., Z. Zhu, J.J Noël and D.W. Shoesmith. 2018. Corrosion of nuclear fuel inside a failed waste container, Encyclopedia of Interfacial Chemistry, 2018, 172–182.

Liu, N., Z. Zhu, L. Wu, Z. Qin, J.J Noël and D.W. Shoesmith. 2019. Predicting radionuclide release rates from spent nuclear fuel inside a failed waste disposal container using a finite element model, Corrosion Journal 75, 302-308.

Liu, N., F. King, J.J Noël and D.W. Shoesmith. 2021. An electrochemical and radiolytic study of the effects of H_2 on the corrosion of UO_2-based materials, Corrosion Science 192 (3), 109776.

MacDonald, N.R., J.J. Day and M.S. Diederichs. 2021a. A Critical Review of Laboratory Multi-Stage Direct Shear Testing for Rock Fractures. GEONiagara – CGS conference 2021.

MacDonald N., J.J. Day and M.S. Diederichs. 2021b. A critical review of multi-stage direct shear testing for rock joints. GeoNiagara: Creating a Sustainable and Smart Future, Canadian Geotechnical Society Annual Conference, 26-29 September 2021.

MacDonald, M., S. Gaines, M.S. Diederichs. 2021c. Estimation of dynamic elastic properties calculated using ultrasonic pulse waves in rock core and comparison to static elastic properties. GEONiagara – CGS conference 2021.

Markus, S., M.S. Diederichs, E. Almog, and A.M.T. Keita. 2021. A Review of Excavation Induced Coupled Consolidation Analysis in Jointed Rock. GEONiagara – CGS conference 2021.

Markus, S. and M.S. Diederichs. 2021. Use of continuum and pseudo-discontinuum FEM models in stepwise verification of the FDEM for simulating damage around tunnels in brittle rock, RocScience International Conference, April 20-21 2021, Toronto, Canada.

Mas Ivars D., M. Pierce, C. Darcel, J. Reyes-Montes, D. Potyondy, R.P. Young, and P.A. Cundall. 2010. The synthetic rock mass approach for jointed rock mass modelling. International Journal of Rock Mechanics and Mining Sciences. 48(2), 219-244. doi:10.1016/j.ijrmms.2010.11.014

Marty, N.C.M., P. Blanc, O. Bildstein, F. Claret, B. Cochepin, D. Su, E.C. Gaucher, D. Jacques, J.-E. Lartigue, K. U. Mayer, J.C.L Meeussen, I. Munier, I. Pointeau, S. Liu and C. Steefel. 2015. Benchmark for reactive transport codes in the context of complex cement/clay interactions, Computational Geosciences, Special Issue on: Subsurface Environmental Simulation Benchmarks. doi: 10.1007/s10596-014-9463-6

Mayer, K.U., E.O. Frind and D.W. Blowes. 2002. Multicomponent reactive transport modelling in variably saturated porous media using a generalized formulation for kinetically controlled reactions. Water Resources Research 38, 1174. doi: 10:1029/2001WR000862

Mayer, K.U. and K.T.B. MacQuarrie. 2010. Solution of the MoMaS reactive transport benchmark with MIN3P - Model formulation and simulation results, Computational Geosciences 14, 405-419. doi: 10.1007/s10596-009-9158-6

Min K-B. and L. Jing. 2003. Numerical determination of the equivalent elastic compliance tensor for fractured rock masses using the distinct element method. International Journal of Rock Mechanics and Mining Sciences. 40(6), 795-816.

Medri, C. 2015. Non-Radiological Interim Acceptance Criteria for the Protection of Persons and the Environment. Nuclear Waste Management Organization Technical Report NWMO TR-2015-03. Toronto, Canada.

Medri, C. 2021. Proposed Post-Closure Non-Radiological Acceptance Criteria for the Protection of Persons and the Environment. Nuclear Waste Management Organization Technical Report NWMO-TR-2021-21. Toronto, Canada.

Mompeán, F.J and H. Wanner. 2003. The OECD Nuclear Energy Agency thermodynamic database project. Radiochimica Acta 91, 617-622.

Nagra, 2019. Implementation of the Full-scale Emplacement Experiment at Mont Terri: Design, Construction and Preliminary Results. Nagra Technical Report 15-02. Wettingen, Switzerland.

NEA. 2018. Metadata for Radioactive Waste Management. Report NEA# 7378. OECD Nuclear Energy Agency. Paris, France.

NEA. 2019a. Preservation of Records, Knowledge and Memory across Generations: Developing a Key Information File for a Radioactive Waste Repository. Report NEA#7377. OECD Nuclear Energy Agency. Paris, France.

NEA. 2019b. Preservation of Records, Knowledge and Memory (RK&M) across Generations: Compiling a Set of Essential Records for a Radioactive Waste Repository. Report NEA#7423. OECD Nuclear Energy Agency. Paris, France.

NEA. 2019c. Preservation of Records, Knowledge and Memory across Generations: Final Report. Report NEA#7421. OECD Nuclear Energy Agency. Paris, France.

NWMO. 2005. Choosing a Way Forward – The Future Management of Canada's Nuclear Fuel – Final Study. Toronto, Canada.

NWMO. 2010. Moving Forward Together: Process for Selecting a Site for Canada's Deep Geological Repository for Used Nuclear Fuel. Toronto. Canada.

NWMO. 2018. Postclosure Safety Assessment of a Used Fuel Repository in Sedimentary Rock. Nuclear Waste Management Organization Technical Report NWMO-TR-2018-08. Toronto, Canada.

NWMO. 2019. RD 2019 – NWMO's Program for research and development for long term management of used nuclear fuel. Nuclear Waste Management Organization Technical Report NWMO-TR-2019-18. Toronto, Canada.

NWMO. 2021a. Implementing Adaptive Phased Management 2021-2025. Toronto, Canada.

NWMO. 2021b. Technical Program for Long-Term Management of Canada's Used Nuclear Fuel - Annual Report 2020. Ed. S. Briggs. Nuclear Waste Management Organization Technical Report NWMO-TR-2021-01. Toronto, Canada.

NWMO. 2021c. Deep Geological Repository Conceptual Design Report Crystalline/Sedimentary Rock. Nuclear Waste Management Organization Report APM-REP-00440-0211-R000. Toronto, Canada.

OHN. 1994. The disposal of Canada's nuclear fuel waste: Preclosure assessment of a conceptual system. Ontario Hydro Nuclear Report N-03784-940010 (UFMED), COG-93-6. Toronto, Canada.

Packulak, T.R.M., J.J. Day, M. T. Ahmed Labeid and M. Diederichs. 2021. New Data Processing Protocols to Isolate Fracture Deformations to Measure Normal and Shear Joint Stiffness. Rock Mech Rock Eng. doi:10.1007/s00603-021-02632-7

Plampin. M. R, Provost A.M, and C.E. Neuzil. 2021 (*in press*). What Causes Underpressures in Multiphase Subsurface Systems? Possible Mechanisms Elucidated by Modeling Southern Ontario. Hydrogeomechanics. Journal of Geophysical Research – Solid Earth.

Poulsen B., D. Adhikary, M. Elmouttie and A. Wilkins. 2015. Convergence of synthetic rock mass modelling and the Hoek–Brown strength criterion. International Journal of Rock Mechanics and Mining Sciences. 80, 171-180.

Racette, J., A. Walker, T. Yang and S. Nagasaki. 2019. Sorption of Se(-II): Batch Sorption Experiments on Limestone and Multi-site Sorption Modelling on Illite and Montmorillonite. Proceedings of 39th Annual Conference of the Canadian Nuclear Society and 43rd Annual CNS/CAN Student Conference. Ottawa, Canada, June 23-29, 2019.

Reijonen, H., T. Karvonen and J.L. Cormenzana. 2014. Preliminary ALARA dose assessment for three APM DGR concepts. Nuclear Waste Management Organization Technical Report NWMO-TR-2014-18. Toronto, Canada.

Reijonen, H., J.L. Cormenzana and T. Karvonen. 2016. Preliminary hazard identification for the Mark II conceptual design. Nuclear Waste Management Organization Technical Report NWMO-TR-2016-02. Toronto, Canada.

Rodriguez, A. and R. Brown. 2021. Preliminary Flood Hazard Assessment at the Ignace Study Area. Nuclear Waste Management Organization Technical Report NWMO-TR-2021-26. Toronto, Canada.

Saito, J., T. Meierbachtol and J. Harper. 2021 (*in review*). Multi-decadal elevation changes of the land terminating sector of West Greenland, Journal of Glaciology.

Schardong, A., P. Breach, J. Kelly and S. Capstick. 2020. Climate Change Impacts on Climate Variables for a Deep Geological Repository (Ignace Study Area). Nuclear Waste Management Organization Technical Report NWMO-TR-2020-04 R001. Toronto, Canada.

Selvadurai, P.A. 2010. Permeability of Indiana limestone: experiments and theoretical concepts for interpretation of results. MEng Thesis, McGill University.

Selvadurai, A.P.S. 2019a. A multi-phasic perspective of the intact permeability of the heterogeneous argillaceous Cobourg limestone, Scientific Reports, 9: 17388. doi:10.1038/s41598-019-53343-7

Selvadurai, A.P.S. 2019b. The Biot coefficient for a low permeability heterogeneous limestone, Continuum Mechanics and Thermodynamics, 31, 939-953. doi:10.1007/s00161-018-0653-7

Selvadurai, A.P.S. 2020 (in press). On the poroelastic Biot coefficient for a granitic rock, Geosciences.

Selvadurai, A.P.S. and P.A. Selvadurai. 2010. Surface permeability tests: Experiments and modelling for estimating effective permeability, Proceedings of the Royal Society, Mathematical and Physical Sciences Series A, 466, 2819-2846.

Selvadurai, A.P.S., A. Blain-Coallier and PA Selvadurai. 2020. Estimates for the effective permeabilities of intact granite obtained from the eastern and western flanks of the Canadian Shield. Minerals: Special Issue on Hydro-Mechanics of Crystalline Rocks, 10(8), 667.

Selvadurai, A.P.S. and S.M. Rezaei Niya. 2020. Effective thermal conductivity of an intact heterogeneous limestone, Rock Mechanics and Geotechnical Engineering, 12, 682-692. doi:10.1016/j.jrmge.2020.04.001

Selvadurai, A.P.S. and A.P. Suvorov. 2020. Influence of pore shape on the bulk modulus and the Biot coefficient of fluid-saturated porous rocks. Scientific Reports, 10:18959.

Selvadurai, A.P.S. 2021. On the poroelastic Biot coefficient for a granitic rock. Geosciences,11, 219. doi:10.3390/geosciences11050219

Seyedi, D.M., C. Plua, M. Vitel, G. Armand, J. Rutqvist, J. Birkholzer, H. Xu, R. Guo, K.E. Thatcher, A.E. Bond, W. Wang, T. Nagel, H. Shao and O. Kolditz. 2021. Upscaling THM modeling from small-scale to full-scale in-situ experiments in the Callovo-Oxfordian claystone. International Journal of Rock Mechanics and Mining Sciences 144: 104582.

Snowdon, A.P., S.D. Normani and J.F. Sykes. 2021. Analysis of Crystalline Rock Permeability Versus Depth in a Canadian Precambrian Rock Setting. JGR Solid Earth, 125(5). doi:10.1029/2020JB020998

Standish, T., J. Chen, R. Jacklin, P. Jakupi, S. Ramamurthy, D. Zagidulin, P. Keech and D. Shoesmith. 2016. Corrosion of copper-coated steel high level nuclear waste containers under permanent disposal conditions. Electrochimica Acta, 211, 331–342.

Standish, T., D. Zagidulin, S. Ramamurthy, P. Keech, D. Shoesmith and J. Noël. 2018. Synchrotron-Based Micro-CT Investigation of Oxic Corrosion of Copper-Coated Carbon Steel for Potential Use in a Deep Geological Repository for Used Nuclear Fuel. Geosciences, 8, 360.

Standish, T.E., L.J. Braithwaite, D.W. Shoesmith and J.J. Noël. 2019. Influence of Area Ratio and Chloride Concentration on the Galvanic Coupling of Copper and Carbon Steel. Journal of The Electrochemical Society, 166, C3448–C3455.

Su, D., K. U. Mayer and K.T.B. MacQuarrie. 2020. Numerical investigation of flow instabilities using fully unstructured discretization for variably saturated flow problems, Advances in Water Resources, 143:103673. doi: 10.1016/j.advwatres.2020.103673

Su, D., K. U. Mayer and K.T.B. MacQuarrie. 2021. MIN3P-HPC: a high-performance unstructured grid code for subsurface flow and reactive transport simulation. Mathematical Geosciences. 53, 517-550.

Tam, J., B. Yu, W. Li, D. Poirier, J-G. Legoux, J.D. Giallonardo, J. Howe, and U. Erb. 2022. The Effect of Annealing on Trapped Copper Oxides in Particle-Particle Interfaces of Cold-Sprayed Cu Coatings. Submitted to Scripta Materialia, 208: 114333.

Tortola M., I.S. Al-Aasm and R Crowe. 2020. Diagenetic Pore Fluid Evolution and Dolomitization of the Silurian and Devonian Carbonates, Huron Domain of Southwestern Ontario: Petrographic, Geochemical and Fluid Inclusion Evidence. Minerals 2020, 10(2), 140. doi: 10.3390/min10020140

Turnbull, J., M. Behazin, J. Smith and P.G. Keech. 2022. The impact of 40 years of radiation on the integrity of copper. Submitted to Journal of Nuclear Materials, 559, 153411.

US DOE. 1994. Airborne release fractions/rates and respirable fractions for non-reactor nuclear facilities. U.S. Department of Energy DOE-HDBK-3010-94. USA.

US DOE. 2007. Preparation of safety basis documents for transuranic waste facilities. U.S. Department of Energy, DOE-STD-5506-2007. USA.

US DOE. 2009. Yucca Mountain Repository SAR. U.S. Department of Energy, DOE/RW-0573, Rev. 1. USA.

Vachon, M.A., K. Engel, R.C. Beaver, G.F. Slater, W.J. Binns, J.D. Neufeld. 2021. Fifteen shades of clay: distinct microbial community profiles obtained from bentonite samples by cultivation and direct nucleic acid extraction, Scientific Reports 11 (1).

Velay-Vitow, J., W. R. Peltier and G. R. Stuhne. 2021. An investigation of the possibility of non-Laurentide ice stream contributions to Heinrich event 3. Quaternary Research, 101, 13-25.

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

Vilks, P. and T. Yang. 2018. Sorption of Selected Radionuclides on Sedimentary Rocks in Saline Conditions – Updated Sorption Values. Nuclear Waste Management Organization Technical Report NWMO-TR-2018-03. Toronto, Canada.

Walker, A., J. Racette, T. Saito, T. Yang and S. Nagasaki. 2021. Sorption of Se(-II) on Illite, MX-80 Bentonite, Shale, and Limestone in Na-Ca-Cl Solutions, Nuclear Engineering and Technology. doi:10.1016/j.net.2021.10.039

Walker, A., J. Racette, J. Goguen and S. Nagasaki. 2018. Ionic Strength and pH Dependence of Sorption of Se(-II) onto Illite, Bentonite and Shale. Proceedings of 38th Annual Conference of the Canadian Nuclear Society and 42nd Annual CNS/CAN Student Conference, Saskatoon, SK, Canada, June 3-6, 2018.

Wilk, L. and G. Cantello. 2006. Used fuel burnups and power ratings for OPG owned used fuel. Ontario Power Generation Report 06819-REP-01300-10121. Toronto, Canada.

Wilk, L. 2013. CANDU fuel burnup and power rating 2012 update. Nuclear Waste Management Organization Technical Report NWMO-TR-2013-02. Toronto, Canada.

Wood. 2019. Climate Change Impacts Review and Method Development. NWMO-TR-2019-05. Toronto, Canada.

Xie, M., P. Rasouli, K.U. Mayer and K.T.B. MacQuarrie. 2014. Reactive Transport Modelling of Diffusion in Low Permeable Media – MIN3P-THcm Simulations of EBS TF-C Compacted Bentonite Diffusion Experiments. Nuclear Waste Management Organization Technical Report NWMO-TR-2014-23. Toronto, Canada.

Xie, M., D. Su, K.U. Mayer and K.T.B. MacQuarrie. 2018. Reactive Transport Modelling Investigation of Elevated Dissolved Sulphide Concentrations in Sedimentary Basin Rocks. Nuclear Waste Management Organization Technical Report NWMO-TR-2018-07, Toronto, Canada.

Xie, M., K.U. Mayer and K.T.B. MacQuarrie. 2021. Reactive Transport Simulations of the Alteration of Interfaces between Bentonite/LHHPC/Host Rock and the Impact on Radionuclide Migration. Nuclear Waste Management Organization Technical Report NWMO-TR-2021-14. Toronto, Canada.

You, C., S. Briggs and M.E. Orazem. 2021. A Mathematical Model for Localized Corrosion of Copper Under a Droplet. In ECS Meeting Abstracts (No. 10, p. 575). IOP Publishing.

Zhu, Z., L. Wu, J.J Noël and D.W. Shoesmith. 2019. Anodic reactions occurring on simulated spent nuclear fuel (SIMFUEL) in hydrogen peroxide solutions containing bicarbonate/carbonate – The effect of fission products. Electrochimica Acta 320, 134546.

Zhu, Z., J.J Noël, D.W. Shoesmith. 2020. Hydrogen peroxide decomposition on simulated spent nuclear fuel in bicarbonate/carbonate solutions. Electrochimica Acta 340, 135980.

Zuo, E., A. Lapp, J. J. Jautzy and I. D. Clark. 2021. Crustal Noble Gas Isotopic Characteristics in Low-Permeability Ordovician Sedimentary Rock, Eastern Flank of the Michigan Basin December 2021, ACS Earth and Space Chemistry doi:10.1021/acsearthspacechem.1c00346

APPENDIX A: NWMO TECHNICAL REPORTS AND REFEREED JOURNAL ARTICLES

A.1 NWMO TECHNICAL REPORTS

Ackerley, N. V. Peci, J. Adams and S. Halchuk. 2021. Seismic Activity in the Northern Ontario Portion of the Canadian Shield: Annual Progress Report for the Period January 1 – December 31, 2019. Nuclear Waste Management Organization Technical Report, NWMO-TR-2021-10. Toronto, Canada.

Chen, Z., P. Hannigan, T. Carter, X. Liu, R. Crowe and M. Obermajer. 2021. A petroleum resource assessment of the Huron Domain. Nuclear Waste Management Organization Technical Report NWMO-TR-2019-20. Toronto, Canada.

Colàs, E., A. Valls, D. García and L. Duro. 2021. Radionuclide Solubility Calculation (Phase 1). Nuclear Waste Management Organization Technical Report NWMO-TR-2021-02. Toronto, Canada.

Gobien, M. and M. Ion. 2021. Nuclear Waste Fuel Projections in Canada – 2021 Update. Nuclear Waste Management Organization Technical Report NWMO-TR-2021-17. Toronto, Canada.

Gobien, M., K. Liberda, and C. Medri. 2021. Fuel Radiotoxicity and Screening Analysis. Nuclear Waste Management Organization Technical Report NWMO-TR-2021-16 R001. Toronto, Canada.

King, F. 2021. Natural Analogues and Their Use in Supporting the Prediction of the Long-Term Corrosion Behaviour of Copper-Coated UFC. Nuclear Waste Management Organization Report Technical Report NWMO-TR-2021-19. Toronto, Canada.

Lampman, T. 2021. Update to Fuel Burnups and Power Ratings. Nuclear Waste Management Organization Technical Report NWMO-TR-2019-04. Toronto, Canada.

Medri, C. 2021. Proposed Post-Closure Non-Radiological Acceptance Criteria for the Protection of Persons and the Environment. Nuclear Waste Management Organization Technical Report NWMO-TR-2021-21. Toronto, Canada.

Rodriguez, A. and R. Brown. 2021. Preliminary Flood Hazard Assessment at the Ignace Study Area. Nuclear Waste Management Organization Technical Report NWMO-TR-2021-26. Toronto, Canada.

Xie, M., K.U. Mayer and K.T.B. MacQuarrie. 2021. Reactive Transport Simulations of the Alteration of Interfaces between Bentonite/LHHPC/Host Rock and the Impact on Radionuclide Migration. Nuclear Waste Management Organization Technical Report NWMO-TR-2021-14. Toronto, Canada.

A.2 REFEREED JOURNAL ARTICLES

Al-Aasm I., R. Crowe and M. Tortola. 2021. Dolomitization of Paleozoic Successions, Huron Domain of Southern Ontario, Canada: Fluid Flow and Dolomite Evolution Water 13 (17), 2449.

Beaver, R.C., K. Engel, W.J. Binns and J.D. Neufeld. 2021. Microbiology of barrier component analogues of a deep geological repository. Can. J. Microbiol. (99) 999, 1-18.

Brooks, G. 2021. Insights into the Connaught sequence of the Timiskaming varve series from Frederick House Lake, northeastern Ontario. Canadian Journal of Earth Sciences, Vol. 58, Number 12.

Diederichs, M., and J. Day. 2021. An illustrative study on the potential sensitivity of predicted long-term EDZ development to, layered and nodular sedimentary structure. Rock Mechanics and Rock Engineering. doi:10.1007/s00603-021-02602-z

Goguen, J., A. Walker, J. Riddoch, S. Nagasaki. 2021. Sorption of Pd on illite, MX-80 and shale in Na-Ca-Cl solutions, Nuclear Engineering and Technology 53 (3), 894-900. doi: doi.org/10.1016/j.net.2020.09.001

Hall, D.S., M. Behazin, W.J. Binns and P.G. Keech. 2021. An evaluation of corrosion processes affecting copper-coated nuclear waste containers in a deep geological repository. Progress in Materials Science, 118, 100766.

Harper, J., T. Meierbachtol, N. Humphrey, J. Saito and A. Stansberry. 2021. Generation and Fate of Basal Meltwater During Winter, Western Greenland Ice Sheet. The Cryosphere, 15, 5409–5421. doi:10.5194/tc-15-5409-2021

Hegger, S., N. Vlacholpoulos and M. Diederichs. 2021a. A New Apparatus for Installing Distributed Optical Sensors onto Uniaxial Compression Test Specimens to Measure Full-Field Strain Responses. Geotechnical Testing Journal 45(1). doi:10.1520/GTJ20210021

Hegger, S., N. Vlachopoulos, T. Poles, and M. Diederichs. 2021b. Measuring the full-field strain response of uniaxial compression test specimens using distributed fiber optic sensing. Rock Mechanics and Rock Engineering. doi:10.1007/s00603-021-02643-4

Innocente, J., M. Diederichs, C. Paraskevopoulou. 2021. Long-term strength; time-dependency; time-dependent cracking; static load testing; Creep; time-to-failure. International Journal of Rock Mechanics and Mining Science. V147. doi:10.1016/j.ijrmms.2021.104900

Jacobsson, L., D. Mas Ivars, H.A. Kasani, F. Johansson and T. Lam. 2021. Experimental program on mechanical properties of large rock fractures, EUROCK 2021, Torino, Italy, 20-25 September 2021, IOP Conf. Ser.: Earth Environ. Sci. 833 012015. doi.10.1088/1755-1315/833/1/012015

Jaquenoud, M., T.E. William, T. Grundl, T. Gimmi, A. Jakob, S. Schefer, V. Cloet, P. De Canniere, L. R. Van Loon and O.X. Leupin. 2021. In-situ X-ray fluorescence to investigate iodide diffusion in opalinus clay: Demonstration of a novel experimental approach, Chemosphere 269, 128674.

Kanik, N.J., F.J. Longstaffe, A. Kuligiewicz and A. Derkowski. (*in press*). Systematics of smectite hydrogen-isotope composition: Structural hydrogen versus absorbed water. Submitted to Applied Clay Science.

Liljedahl, L. C., T. Meierbachtol, J. Harper, D. van As, J.O. Näslund, J.O. Selroos, J. Saito, S. Follin, T. Ruskeeniemi, A. Kontula and N. Humphrey. 2021. Rapid and sensitive response of Greenland's groundwater system to ice sheet change. Nature Geoscience. 14(10), 751-755. doi:10.1038/s41561-021-00813-1

Li, W., B. Yu, J. Tam, J.D. Giallonardo, D. Poirier, J.-G. Legoux, P. Lin, G. Palumbo and U. Erb. 2020. Microstructural Characterization of Copper Coatings in Development for Application to Used Nuclear Fuel Containers. Journal of Nuclear Materials, 532, p.152039.

Liu, N., F. King, J.J Noël and D.W. Shoesmith. 2021. An electrochemical and radiolytic study of the effects of H_2 on the corrosion of UO_2-based materials, Corrosion Science 192 (3), 109776.

Packulak, T.R.M., J.J. Day, M. T. Ahmed Labeid and M. Diederichs. 2021. New Data Processing Protocols to Isolate Fracture Deformations to Measure Normal and Shear Joint Stiffness. Rock Mech Rock Eng. doi:10.1007/s00603-021-02632-7

Selvadurai, A.P.S. 2021. On the poroelastic Biot coefficient for a granitic rock. Geosciences,11, 219. doi:10.3390/geosciences11050219

Seyedi, D.M., C. Plua, M. Vitel, G. Armand, J. Rutqvist, J. Birkholzer, H. Xu, R. Guo, K.E. Thatcher, A.E. Bond, W. Wang, T. Nagel, H. Shao and O. Kolditz. 2021. Upscaling THM modeling from small-scale to full-scale in-situ experiments in the Callovo-Oxfordian claystone. International Journal of Rock Mechanics and Mining Sciences 144, 104582.

Snowdon, A.P., S.D. Normani and J.F. Sykes. 2021. Analysis of Crystalline Rock Permeability Versus Depth in a Canadian Precambrian Rock Setting. JGR Solid Earth, 125(5). doi:10.1029/2020JB020998

Su, D., K. U. Mayer and K.T.B. MacQuarrie, 2021. MIN3P-HPC: A High-Performance Unstructured Grid Code for Subsurface Flow and Reactive Transport Simulation. Mathematical Geosciences, 53, 517-550.

Tam, J., W. Li, B. Yu, D. Poirier, J-G. Legoux, P. Lin, G. Palumbo, J.D. Giallonardo and U. Erb. 2020. Reducing Complex Microstructural Heterogeneity in Electrodeposited and Cold Sprayed Copper Coating Junctions. Surface and Coatings Technology, Vol. 404, p.126479.

Turnbull, J., M. Behazin, J. Smith and P.G. Keech. 2022. The impact of 40 years of radiation on the integrity of copper. Submitted to Journal of Nuclear Materials, 559, 153411.

Vachon, M.A., K. Engel, R.C. Beaver, G.F. Slater, W.J. Binns, J.D. Neufeld. 2021. Fifteen shades of clay: distinct microbial community profiles obtained from bentonite samples by cultivation and direct nucleic acid extraction, Scientific Reports 11 (1).

Velay-Vitow, J., W. R. Peltier and G. R. Stuhne. 2021. An investigation of the possibility of non-Laurentide ice stream contributions to Heinrich event 3. Quaternary Research, 101, 13-25.

Walker, A., J. Racette, T. Saito, T. Yang and S. Nagasaki. 2021. Sorption of Se(-II) on Illite, MX-80 Bentonite, Shale, and Limestone in Na-Ca-Cl Solutions. Nuclear Engineering and Technology. doi:10.1016/j.net.2021.10.039

Zuo, E., A. Lapp, J. J. Jautzy and I. D. Clark. 2021. Crustal Noble Gas Isotopic Characteristics in Low-Permeability Ordovician Sedimentary Rock, Eastern Flank of the Michigan Basin December 2021. ACS Earth and Space Chemistry. doi:10.1021/acsearthspacechem.1c00346