Technical Program for Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2024

NWMO-TR-2025-01 November 2025

Nuclear Waste Management Organization
(J. Freire-Canosa, ed.)

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ABSTRACT

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Abstract

This report is a summary of activities and progress in 2024 for the Nuclear Waste Management Organization's Technical Program for the long-term management of Canada's 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 with a particular focus in assessing the two remaining siting areas. This effort culminated with the selection of the Revell site for the used fuel Deep Geological Repository (DGR) with the potential host communities Wabigoon Lake Ojibway Nation and the Township of Ignace agreeing to move forward into the regulatory approvals process.

NWMO continued to participate in international research activities, including projects associated with the Posiva Encapsulation Plant for spent nuclear fuel, the Mont Terri Underground Rock Laboratory, the ONKALO facility, the Grimsel Test Site and the OECD Nuclear Energy Agency.

NWMO's technical program supported technical presentations at national and international conferences, issued 6 NWMO technical reports, published 31 journal articles and presented 21 technical papers in several international conferences.

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1 INTRODUCTION

The Nuclear Waste Management Organization (NWMO) is implementing Adaptive Phased Management (APM) for the long-term management of used nuclear fuel. 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.

On November 28, 2024, Wabigoon Lake Ojibway Nation (WLON) and the Township of Ignace agreed to move into the regulatory decision-making phase as potential host communities for a deep geological repository for Canada's used nuclear fuel.

Both the Township of Ignace and Wabigoon Lake Ojibway Nation completed their own community-driven willingness processes, and the outcome of both was a compelling demonstration of willingness to move forward in the site selection process (see Figure 1-1).

The process for selecting a site was described in *Moving Forward Together: Process for Selecting a Site for Canada's Deep Geological Repository for Used Nuclear Fuel* (NWMO 2010). The steps leading to the selection of the site included the evaluation of the geological suitability of 22 willing and informed host communities that came forward to be considered as potential hosts of the DGR. The evaluations consisted 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. Reports documenting the site selection process are available on the NWMO website. https://www.nwmo.ca/Documents-and-reports

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 1-2 for a generic rock setting (the design will be varied for actual rock conditions).

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 partnerships with communities. This report summarizes technical work conducted in 2024 supporting the selection of the Revell site in the Wabigoon Lake Ojibway Nation and Ignace area and, in the longer term, the impact assessment and licence applications for the chosen site. NWMO's overall implementation plan is described in *Implementing Adaptive Phased Management* 2024-2028 (NWMO 2024).

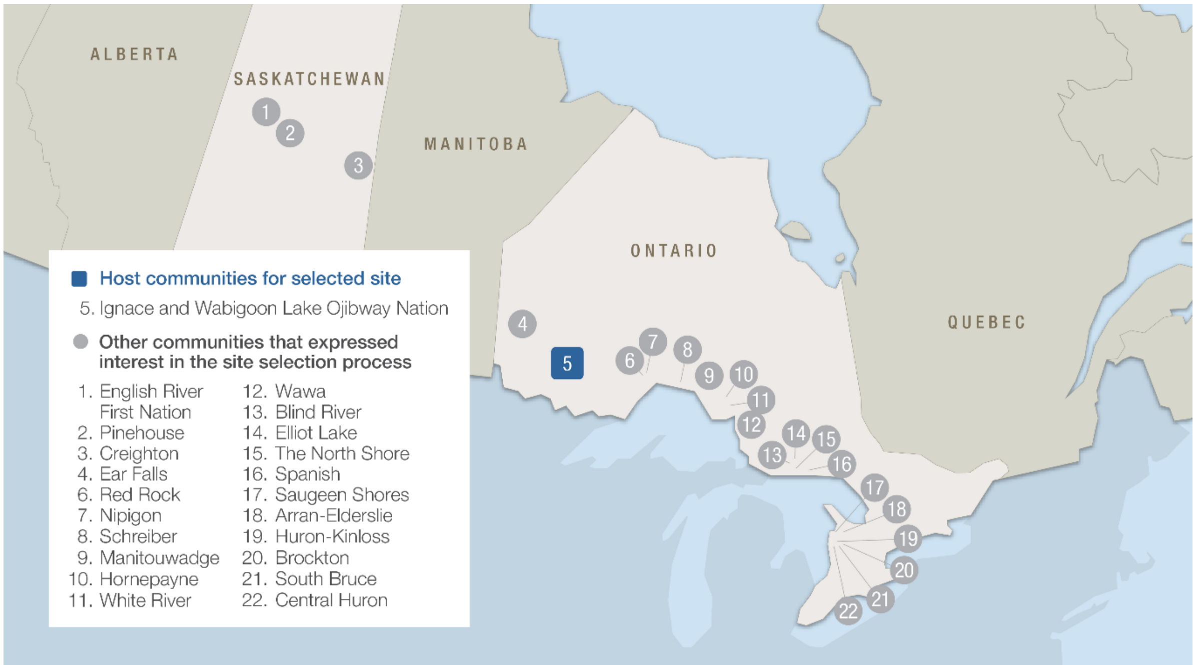


Figure 1-1: Selected Site and Communities that Participated in the Site Selection Process.

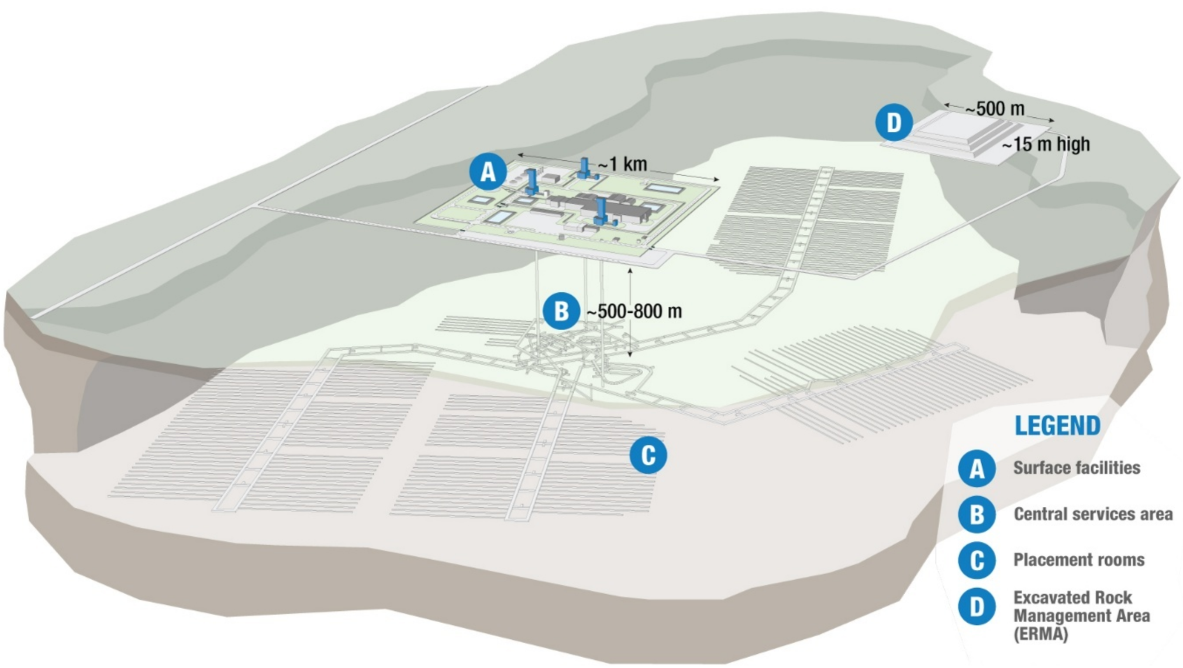


Figure 1-2: Illustration of a Deep Geological Repository Reference Design

2 OVERVIEW OF NWMO TECHNICAL PROGRAMS

The NWMO Technical Program includes site investigations, preliminary design and proof testing, and developing the safety case for a used fuel DGR. Work conducted during 2024 is summarized in this report. Prior years work is summarized in the 2023 version of the Annual Technical Report (NWMO 2023a).

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

This work involved 17 universities (including 15 Canadian universities), as well as a variety of industrial and governmental research partners. A listing of the 2024 NWMO work in the form of technical reports, journal articles and conference papers can be found in Appendices A1, A2 and A3, respectively.

An important aspect of the NWMO's technical program is collaboration with radioactive waste management organizations in other countries. In 2024, the NWMO entered into new Agreements with the Australian Radioactive Waste Agency (ARWA) and the Korean Atomic Energy Research Institute (KAERI) and renewed agreements with the Korean Radioactive Waste Agency (KORAD) and the National Atomic Research Institute (NARI) in the Republic of China (Taiwan). The NWMO also continued its participation in the previous agreements with the United States Department of Energy (USA/DOE), ANDRA (France), Nagra (Switzerland), NWS (United Kingdom), NUMO (Japan), ONDRAF (Belgium), Posiva (Finland) and SKB (Sweden) to exchange information arising from their respective national programs to develop a deep geologic repository for nuclear waste and collaborated with other organizations on specific projects.

Some of this collaboration is work undertaken at underground research facilities. In 2024, 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 2024:

- 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, DR-E),
    - 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),

- o Hydrogen Transfer (HT) test,
- o Long-term FE-M Project and Pressure Monitoring (LP-A),
- o Microbial Activity (MA),
- o Porewater Gas-characterisation Methods for Reactive and Noble Gases (PC-D),
- o Seismic imaging ahead of and around underground infrastructure (SI-A),
- o Nanoseismic Monitoring (SM-C) Experiment,
- o Permanent nanoseismic monitoring (SM-C),
- o POST Project (Fracture Parameterization for Repository Design & Post-closure Analysis),
- o Materials Corrosion Test (MaCoTe) at GTS, and
- o Gas-Permeable Seal Test (GAST) at GTS.

NWMO was involved with the following modelling or information exchange projects in 2024:

- DECOVALEX thermal-hydraulic-mechanical modelling,
- Post-closure criticality working group,
- CatchNET Project on cold climate hydrology modelling,
- BIOPROTA biosphere modelling, and
- Joint projects with SKB on modelling fractured rock, including HM coupling, Skempton/Biot coefficient and 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),
- Thermochemical Database (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 2024, research and development progressed as planned in the Engineering Program:

1. Work continued on the preparation of the UFC Conceptual Design Report for the Mark II Reference UFC.

2. Supply chain capacity for copper coating services for Mark II UFC was augmented through the completion of qualification activities at a commercial electrodeposition contractor.

3. Assessment of primary and alternative routes to the potential DGR sites of Revell and South Bruce continued.

4. Work continued on the Used Fuel Packaging Plant (UFPP) on technical feasibility and risk assessment as part of the next phase of the facility design to support the Impact Assessment and initial licence application activities.

5. Assessment of potential underground DGR layouts continued for the two potential sites at Revell (crystalline rock) and South Bruce (sedimentary rock).

6. A study was completed assessing three transfer equipment concepts for the Loaded Buffer Box Transfer Cask to select a preferred option.

7. Received a multi-year grant awarded by NRCan for a program entitled "*Using Adaptive Phased Management to Enable SMRs in Canada."* This program was developed to study an alternate EBS design concept (Mark I Long UFC) to accommodate both SMR and CANDU fuel waste.

Summaries of these activities in 2024 are provided in the following sections.

3.1 USED FUEL TRANSPORTATION

3.1.1 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 interim storage facilities to the Deep Geological Repository (DGR).

The repository location was selected in November 2024 and is sited in crystalline rock located in Northwestern Ontario, specifically the Revell site in the Wabigoon Lake Ojibway Nation territory and Ignace area. Used fuel will be transported from the various interim storage facilities to the DGR site as illustrated in Figure 3-1.

Figure 3-1: Interim Storage Facilities and DGR Site

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) to transport used fuel stored in storage modules and Basket Transportation Packages (BTPs) for used fuel stored in baskets. 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 Packages (DSC-TPs) for the transport of OPG used fuel currently stored in Dry Storage Containers (DSCs). Superload or heavy-haul trucks and railcars are being considered for these DSC-TP shipments. As in the reference UFTS, BTPs are to be used to transport non-OPG owned fuel, using 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 related to transportation emergency management (see Section 3.2.2 for details), decontamination and decommissioning of transportation packages (see Section 3.2.3 for details) as well as supporting the Whiteshell Fuel Transfer Project (see Section 3.2.4 for details) were all areas of work in 2024.

3.1.2 Transportation Emergency Management Framework

As part of moving fuel, NWMO must have a comprehensive transportation emergency management system in place that interfaces with the established local, provincial and federal systems. In 2024, NWMO completed a study which developed information upon which an emergency management framework for the transport of Canada's used nuclear fuel can be developed. This work identified and highlighted relevant regulatory and legislative requirements and identified key provisions and emergency management elements (preparedness, response and recovery) that NWMO will need to consider as it establishes its emergency management program for the transport of used fuel. This work leveraged industry expertise regarding the processes involved during the identification and response to emergency situations during transport. The scope of this study included both road and rail modes of transportation, and considered federal, provincial, and local requirements for emergency response to incidents involving Class 7 (radioactive) dangerous goods such as used nuclear fuel.

3.1.3 Transportation Related Decontamination and Decommissioning

During the transportation campaign, the NWMO is responsible for ensuring that potential contamination and dose limits meet regulatory requirements to ensure the safety and protection of workers, the public and the environment. Furthermore, the NWMO will be responsible for decommissioning transportation packages at their end of life. As such, in 2024, NWMO initiated work to assess decontamination and decommissioning strategies for transportation packages. This work is expected to conclude in 2025.

3.2 USED FUEL PACKAGING PLANT

The Used Fuel Packaging Plant (UFPP) will be a key part of the APM DGR facility, and will include all necessary structures, systems, and components for: (1) Receiving used fuel transportation packages; (2) Loading used fuel into a long-lived disposal container called the Used Fuel Container (UFC); and (3) Sealing, inspecting, and dispatching filled UFCs for underground placement. There are currently two types of fuel casks envisioned for the transportation fleet that may be received at the UFPP, corresponding to the interim storage method used at the generating stations: (1) Used Fuel Transportation Packages (UFTP) for fuel stored in modules, and (2) Basket Transportation Packages (BTP) for fuel stored in sealed baskets.

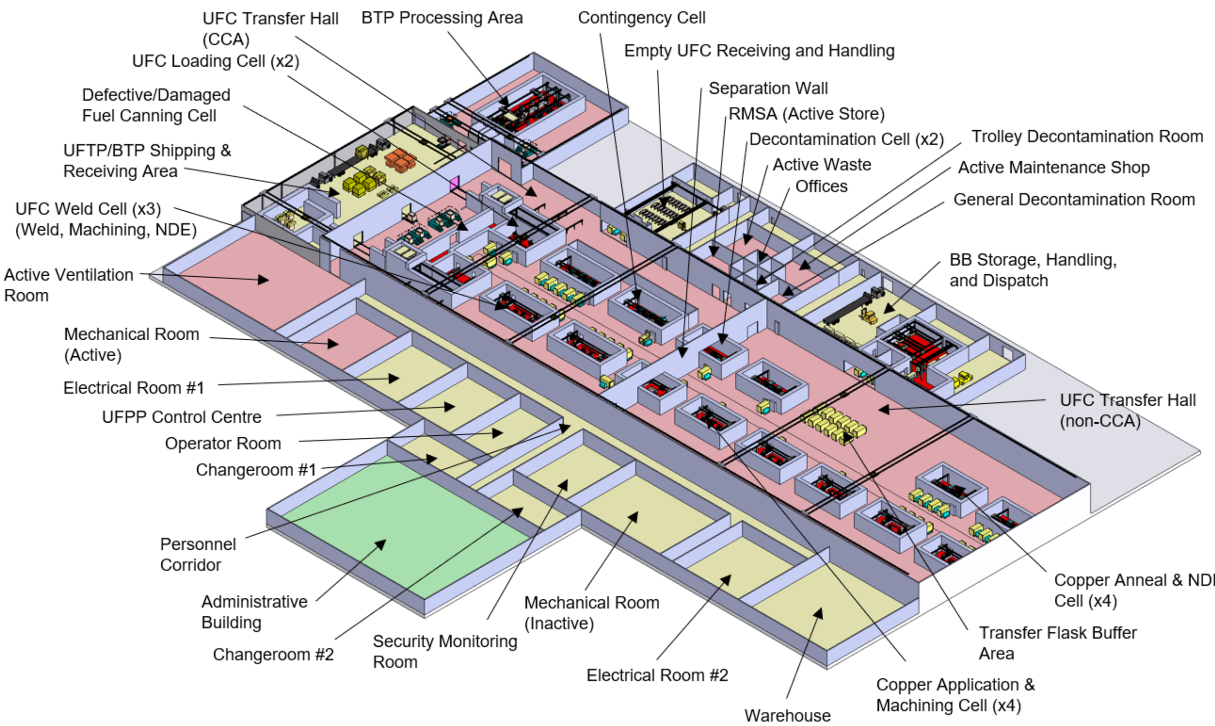


Figure 3-2: Concept Layout of the Used Fuel Packaging Plant (UFPP)*

*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 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).

The used fuel packaging process and UFPP design continue to mature alongside the packaging technology and UFC design. Twelve key process systems have been identified at this time: (1)

transportation package receipt; (2) used fuel storage; (3) used fuel inspection; (4) UFC handling; (5) UFC welding; (6) weld machining; (7) weld NDE; (8) copper application; (9) copper heat treatment; (10) copper machining; (11) copper NDE; (12) loaded buffer box assembly and dispatch.

Design development work packages for the UFPP that were started in 2023 continued through 2024, with two specific aims: (1) generation of conceptual-level engineering documentation and summary reports to support the Impact Assessment and License to Prepare Site Applications; and (2) advancement of the technical design in selected areas for the UFPP. Details for this work are provided in the subsections below.

3.2.1 Support of Impact Assessment and Initial Licence Activities

The preparation for additional work packages to support the Impact Assessment (IA) and initial licence activities continued in 2024. NWMO’s engineering teams generated a consolidated data tracking system containing all the data inputs requested from engineering for the IA and initial licence application submissions. Over 3,000 data inputs were captured as part of this planning work. This effort integrates all design work packages so that all engineering inputs for the IA and initial licence application will be aligned. The engineering groups, working together, identified already completed documents or identified gaps in the information necessary to address each requested input. Through workshops and discussion, the data input requestors and the engineering groups collaboratively clarified and recorded the path forward to address each requested input. It was determined that objectives for approximately 1,900 engineering inputs had already been met, with 1,100 remaining inputs identified for future work.

These 1,100 remaining engineering inputs still required by the data requestors resulted in 21 new or updated Mining and Repository Engineering (MRE) and UFPP work packages. An integrated schedule was developed to map out the 21 work packages over three phases that will persist through 2025. The integrated schedule was substantially developed in 2024, and completion is expected in early 2025. The integrated schedule development precedes the launch of the 21 identified work packages. Most of these work packages were launched by the end of 2024 with the remaining expected to kick-off in early 2025.

Many of the work packages integrate MRE work with UFPP work. The UFPP-only work packages that were updated to support IA and initial licence application are described in Sections 3.3.4, 3.3.5, 3.3.6 below.

Scheduling and procedure optimization with consultants continues in parallel with the start of the work packages. These efforts are to help the involved teams align with an aggressive schedule to support regulatory requirements, including baseline environmental studies and initial project description. These studies and documents will be inputs to the planned IA and initial licence application submissions.

3.2.2 Active Waste Management Systems

The active solid and liquid waste management systems within the UFPP collect and process active solid and liquid waste that is generated during UFPP operations and maintenance. The conceptual design of the Active Solid Waste Management System (ASWMS) and Active Liquid Waste Management System (ALWMS) was completed in 2024 with industrial partners to support the preparation of IA and initial licence application inputs.

The design of the ASWMS is based on active solid waste estimates from previously completed work. Based on the waste types, volumes and rates, the ASWMS is designed to collect, classify, process (cut and compact) and package waste to be transferred to the DGR Low and Intermediate Level Waste Interim Storage Facility (LILWSF). The conceptual design of the ASWMS includes a Design Requirements document, Design Description, General Arrangement drawing, Process Flow diagrams, and Summary Sheet.

Similarly, the ALWMS is designed based on previously completed work which evaluated the sources of active liquid waste and estimated total amount that would be produced in the UFPP during the operations phase. The ALWMS is designed to collect, treat and monitor all active liquid waste. ALWMS liquid treatment process systems include tanks, pumps, chemical injection nozzles, filtration vessels, and ion exchangers. Treated liquid waste is sent to a verification tank where its activity and contaminant levels are measured to confirm all treated water meets regulatory requirements and can be discharged to the Inactive Waste Management System. The conceptual design of the ALWMS included a Design Requirements document, Design Description, General Arrangement drawing, Process Flow diagrams, and Summary Sheet.

3.2.3 Active Ventilation and HVAC Systems

The integrated Active Ventilation and HVAC (Heating, Ventilation, and Air Conditioning) systems are crucial for safe operation of the Used Fuel Packaging Plant. NWMO completed conceptual design of these systems in 2024 with industrial partners to support the preparation of IA and initial licence application inputs. System equipment layouts were generated, including fans, make-up air units, air handling units, duct routing, control dampers, boilers, unit heaters, filter stages, and other associated components. These designs allowed the team to estimate the material quantities needed for initial construction of these systems, as well as emissions, wastes, and utilities required for operations and maintenance.

The HVAC system provides heating and cooling for air in the UFPP to accommodate external weather conditions, and the heat load from equipment and personnel.

The Active Ventilation system is designed to maintain containment of radioactive contamination in each hot cell and functional area of the UFPP by ventilating air through a specialized exhaust system while maintaining a low pressure (i.e., depression) in each area relative to the ambient external atmosphere. A cascade ventilation design approach ensures that air always flows from the lower risk areas into the higher risk areas. Air entering the UFPP and subsequently exhausted from the controlled areas passes through several stages of filtration, including coarse filters, HEPA (High Efficiency Particulate Air) filters and HEGA (High Efficiency Gas Adsorber) filters. The classification of each area in the UFPP and the assignment of ventilation rates and depressions is based primarily on the international best practice documented in standard *ISO-17873 Nuclear facilities: Criteria for the design and operation of ventilation systems for nuclear installations other than nuclear reactors*.

3.2.4 UFPP Plant Infrastructure and Building Systems

The Infrastructure and Building Systems component of the UFPP design has been completed. This work package delivers a first iteration of the building’s structural design and includes a preliminary collection of the applicable codes and standards for the facility. It also outlines the industry best practices for the design and construction of the building structure.

The plant infrastructure refers to the floors, foundations, walls (both internal and external), ceilings/roofs and the supports holding these elements. Internal walls include shielded and non-shielded partitions. External walls are the partitions that protect the UFPP internal systems from the elements (e.g. weather) and the shielded walls which protect the environment from the internal hazards of the UFPP. The building systems refer to building-wide systems which are necessary for building functionality and safety including drainage and fire suppression systems.

This sub-work package has led to a 25% reduction on the expected facility height, helping demonstrate advancement of the UFPP design.

3.2.5 UFPP Operations Plan

The UFPP Operations Plan will summarize all normal operations that will occur in the UFPP during the operations phase of the project. This includes the primary processes, such as receipt of the fuel at the UFPP, repackaging the fuel into UFCs, and assembly of a loaded buffer box (LBB). It will also describe maintenance operations for the UFPP primary process systems, and the support facilities such as the Active Liquid Waste Management System (ALWMS), Active Solid Waste Management System (ASWMS), Active Ventilation and HVAC System, and Transportation Package Decontamination System. Lastly, the report will address personnel requirements for the operations phase and provide justification for the additional areas added to the plant through the update of the UFPP General Arrangement Drawing.

3.2.6 UFPP Construction Plan

The UFPP Construction Plan will outline the preparation and execution phases of the UFPP construction at a level suitable to support the IA and initial licence application. This plan will include construction requirements development, a construction schedule, and a description of the execution. A key objective of this work is to establish reasonable milestone dates for the start and completion of UFPP construction. This established construction schedule will help ensure that adequate time is allocated for UFPP construction, commissioning, worker training, and production ramp up to full operations. The UFPP construction will be concurrent with the development and construction of multiple other DGR facilities. The UFPP Construction Plan will be aligned with MRE’s Construction Plan to ensure coordination across activities.

3.2.7 UFPP Decommissioning Plan

This work package will assess the different decommissioning strategies for the UFPP and then develop a Conceptual Decommissioning Plan that aligns with the selected strategy. The strategy selection will study advantages and disadvantages of various decommissioning approaches and chronologies. Consideration will be given to immediate (prompt) and deferred decommissioning strategies, and evaluation criteria will be based on OPEX from similar facilities.

Once a decommissioning strategy is selected, a Conceptual Decommissioning Plan will be developed to outline the schedule and activities that must be completed to decommission the UFPP. The report will follow selected sections from REGDOC-2.11.2: Waste Management Decommissioning (CNSC 2021a), as this will become an input to the Preliminary Decommissioning Plan (PDP) which will be developed in the future.

Following the Conceptual Decommissioning Plan, a UFPP Decommissioning Plan Waste Report will summarize all active, inactive and hazardous waste that will be generated from the

UFPP decommissioning activities. This will provide an input to the underground co-emplacement design and safety assessment work.

3.2.8 UFPP Class 4 Cost Estimate

UFPP Class 4 Cost Estimate supports the overall Lifecycle Cost Estimate (LCE) report, which NWMO is responsible to periodically update for its sponsors (i.e. OPG, HQ, NBP, AECL). The LCE describes all the work NWMO intends to complete to meet the obligations. This work package will ensure alignment with the latest reference design for the UFPP. The finalized cost estimate will serve as an input for 2026 LCE development. The estimate process will follow AACE 18R-97 and 115R-21 as guidance, and a variance report will document all adjustments made throughout the process. A sensitivity analysis will also examine the potential impacts on the LCE by increasing the total lifetime fuel bundle UFPP throughput.

3.2.9 Collaboration with Posiva Solutions Oy Finland

The ONKALO disposal facility in Finland developed by Posiva is the world’s first deep geological repository for spent nuclear fuel. Posiva has accumulated over 40 years of engineering research and development experience in used fuel packaging for their facility, which encompasses both the canister design and the machinery for safely handling the fuel during the packaging process.

The ONKALO encapsulation plant is the system that will be used to package Finland’s used fuel into their long-lived KBS-3 disposal canister, and the functions of this plant are comparable to the NWMO UFPP. The civil construction and equipment installation at the ONKALO encapsulation plant has been completed in 2024.

Posiva started the Trial Run of Final Disposal (TRFD) in 2024, during which they test the joint functionality of all the equipment, systems, processes, and their organisation. NWMO subject matter experts, including a UFPP senior engineer, attended the TRFD in October 2024 and participated in workshops focusing on lessons learned regarding the ONKALO encapsulation plant design, construction, commissioning and operations.

NWMO also continued a collaborative project with Posiva to leverage the accumulated knowledge from their technical experts. This experience is being applied to our designs to improve the safety, efficiency, and reliability of used fuel packaging in Canada. Ongoing work packages related to Posiva system documentation and expert review of NWMO design requirements continued in 2024. A new body of work was also added, focusing on the details of the Posiva encapsulation plant processes and lifecycle cost model.

3.2.10 Fuel Receipt Logistics Study

In 2024 a preliminary scoping study was initiated in collaboration with Ontario Power Generation to examine the impact of receiving CANDU fuel with varying ages and selectively loading a mix of ages into the UFCs that are processed in the UFPP. For example, if NWMO were to receive younger fuel that has cooled for 10 years in the wet fuel bays with fuel that has cooled for 40 years in both wet and dry storage systems. This may require some changes to the UFPP structures, systems, and components. The purpose of the study was to begin examining such potential impacts.

3.3 BUFFER AND SEALING SYSTEMS

The NWMO concluded the Buffer and Sealing Systems Proof Test Program in 2022 and summarized its findings and recommendations for further work. The findings and recommendations were reviewed in 2023 and work progressed to plan a second emplacement trial to test equipment for in-situ Gap Fill Material density measurement which was conducted in 2024.

3.3.1 Emplacement Trial of Modified Emplacement Room

Prior to the trial, variations in the shape of the wall of the mock emplacement room were made by removing some of the material to simulate rock spalling that may occur during drill and blast excavation. Two features were examined: a shallow, smooth feature at the ceiling of the room and a deep, block-like rectangular feature in the upper portion of one of the sidewalls. Following placement of steel boxes of the dimension of the bentonite block that will encase the container (see Figure 1-2) granular bentonite was loaded into the region between the boxes and simulated rock wall. Both *in situ* and *ex situ* measurements of the density of the granular bentonite showed that room average density of the bentonite was sufficient to meet specifications. However, these measurements also showed inhomogeneity within the granular bentonite. Post experimental analysis of the results suggested that the augers utilized for the trial may be undersized for filling larger features such as rock spalls. Notably, the equipment was not set up to allow for unequal bentonite flow from one side of the room to the other to accommodate irregularities such as rock spalls. This feedback will be incorporated into future emplacement trials.

3.4 SITE AND REPOSITORY

3.4.1 Shafts, Headframes, and Hoisting Systems

The pre-feasibility level of design for the shaft, headframe, and hoisting plant at the Revell site is completed. The underground repository which is approximately 500 to 800 meters below average ground surface will be supported by three shafts: Exhaust Ventilation Shaft, Service Shaft and Main Shaft.

The Exhaust Ventilation Shaft (EVS) (Figure 3-3) will feature an auxiliary cage for separate escapement from the repository to surface, as well as a winch platform for shaft maintenance. The shaft will have an inside diameter of 7 m with a 500 mm thick concrete liner and will handle most of the repository exhaust air. It is divided into two compartments for the auxiliary cage and winch platform. The auxiliary cage and the winch platform are guided on fixed steel guides connected to steel buntons at 6 m intervals.

The EVS will be equipped with a ground mounted single drum Blair Multi-Rope (BMR) hoist with a single cage conveyance. The hoist plant is designed for a 3.9 tonne cage capacity with a designed travel speed of 2.5 m/s. The headframe is a steel structure with nomically 51 m tall.

Once shaft sink is completed, two of the sinking winches will be reconfigured for the winch platform, which will be used for lowering equipment during initial development and for permanent access to shaft services. The platform design is currently at a conceptual level, and future study is required.

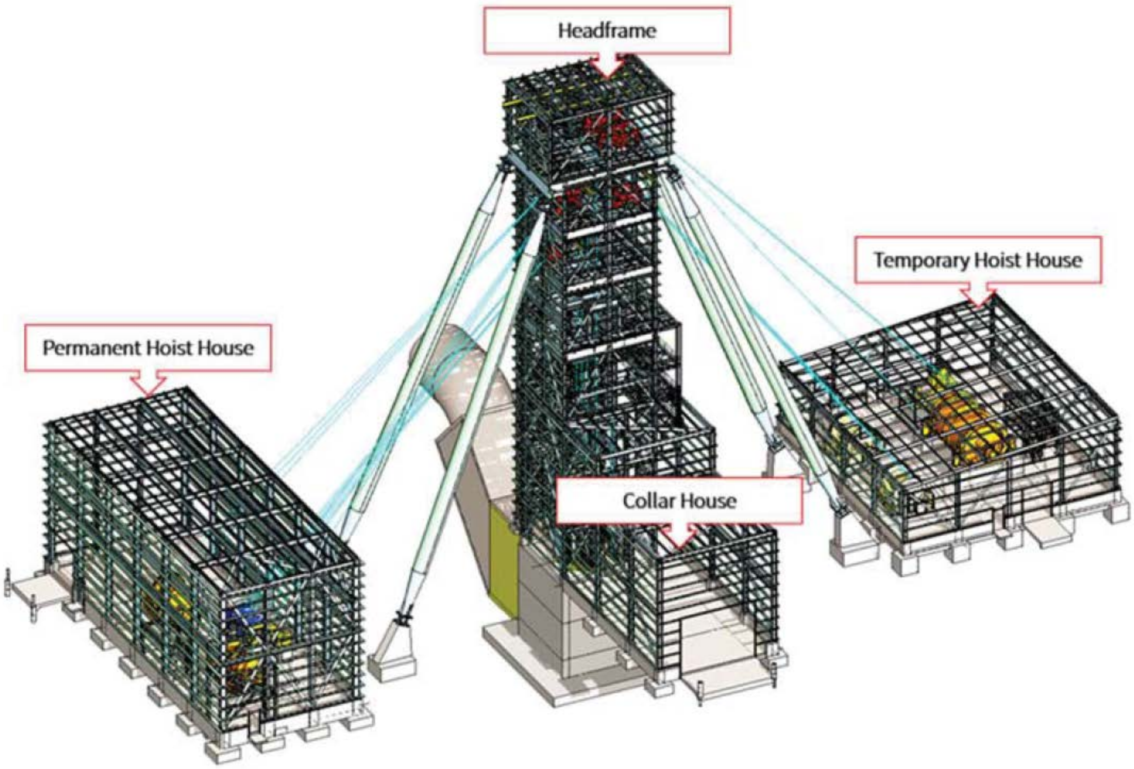


Figure 3-3: Exhaust Ventilation Shaft Surface Plant – Temporary Configuration

The Service Shaft (Figure 3-4) will feature a service cage and an auxiliary cage for movement of personnel and non-nuclear material into and out of the repository, as well as a skip for movement of excavated rock to surface. The shaft will have an inside diameter of 7 m with a 500 mm thick concrete liner and will handle all of the repository fresh air. It is divided into three compartments for the skip, service cage, and auxiliary cage. The conveyances are guided on fixed steel guides connected to steel buntons at 6 m interval.

Three (3) ground mounted BMR hoists will be located in a hoist house adjacent to a steel headframe which will have a nominal height of 55 m. The service cage hoist is designed for a 12-tonne cage capacity with a designed travel speed of 2.5 m/s. The skip hoist is designed for a single14-tonne skip with a designed travel speed of 5 m/s. And the auxiliary hoist is designed for a 3.9-tons cage capacity with a designed travel speed of 2.5 m/s.

The bin house is a building attached to the headframe which contains a 400 tonne-capacity bin and truck chute. Excavated rock from the skip is dumped into the bin which provides temporary storage. A truck chute on the bottom of the bin is then used to load haul trucks below.

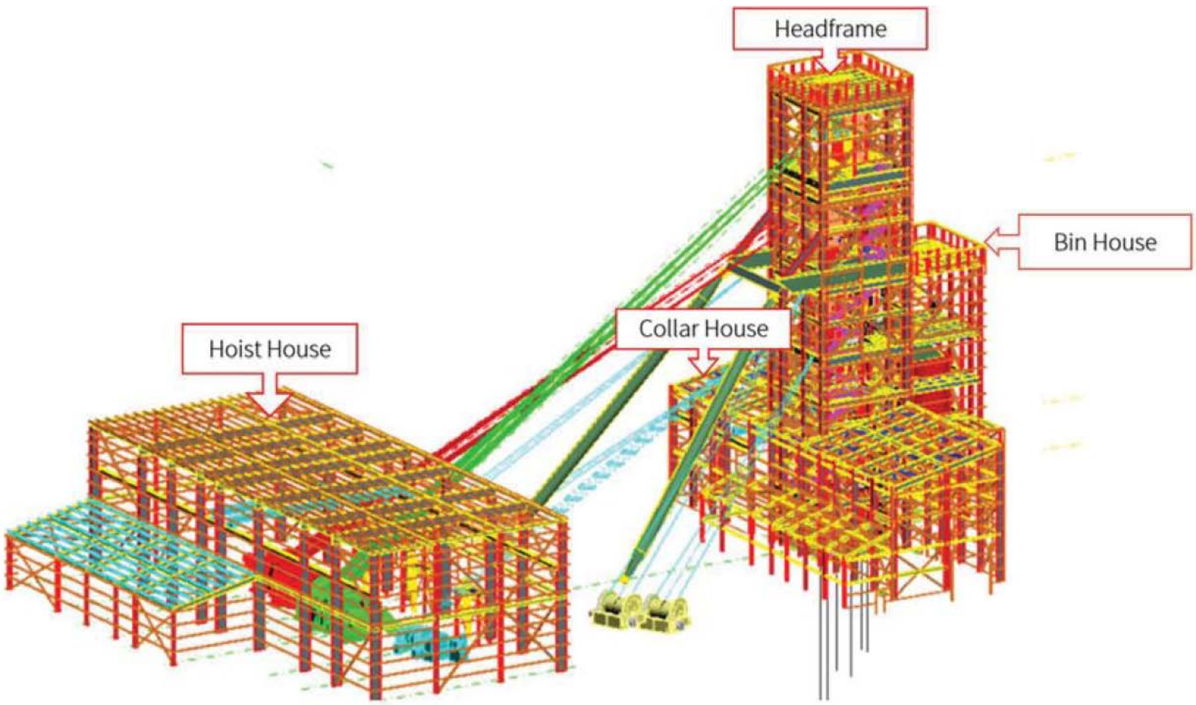


Figure 3-4: Service Shaft Surface Plant

The Main Shaft (Figure 3-5) will feature a cage and counterweight for surface to underground transfer of the Loaded Buffer Boxes (LBB). The shaft will have an inside diameter of 7 m with a 500 mm thick concrete liner. It is divided into three compartments for the main cage, counterweight, and shaft services. The conveyances are guided on fixed steel guides connected to steel buntons at 6 m intervals.

A single ground mounted Koepe hoist will be located in a hoist house adjacent to the steel headframe which will have a nominal height of 47 m. The main shaft cage hoist is designed for a 65-tonne cage capacity with a designed travel speed of 2.5 m/s.

A shaft sinking methodology was developed to form the basis of the sinking schedule and describe the overall shaft sinking activities including shaft collar construction, pre-sink, shaft sinking plant and equipment, full sink to shaft bottom, shaft station and bottom excavation, and shaft changeover.

During shaft sinking, the effective work time per 12-hours shift is estimated to be 10.5 hours, based on a two 12-hours shifts schedule, operating seven days per week. The shaft sinking cycle time was calculated based on each sinking-related activity. The shaft sinking durations, including pre-sink, full sink, allowances for geoscience verification and grouting programs, and off-shaft development, were estimated using available information to support the construction schedule development.

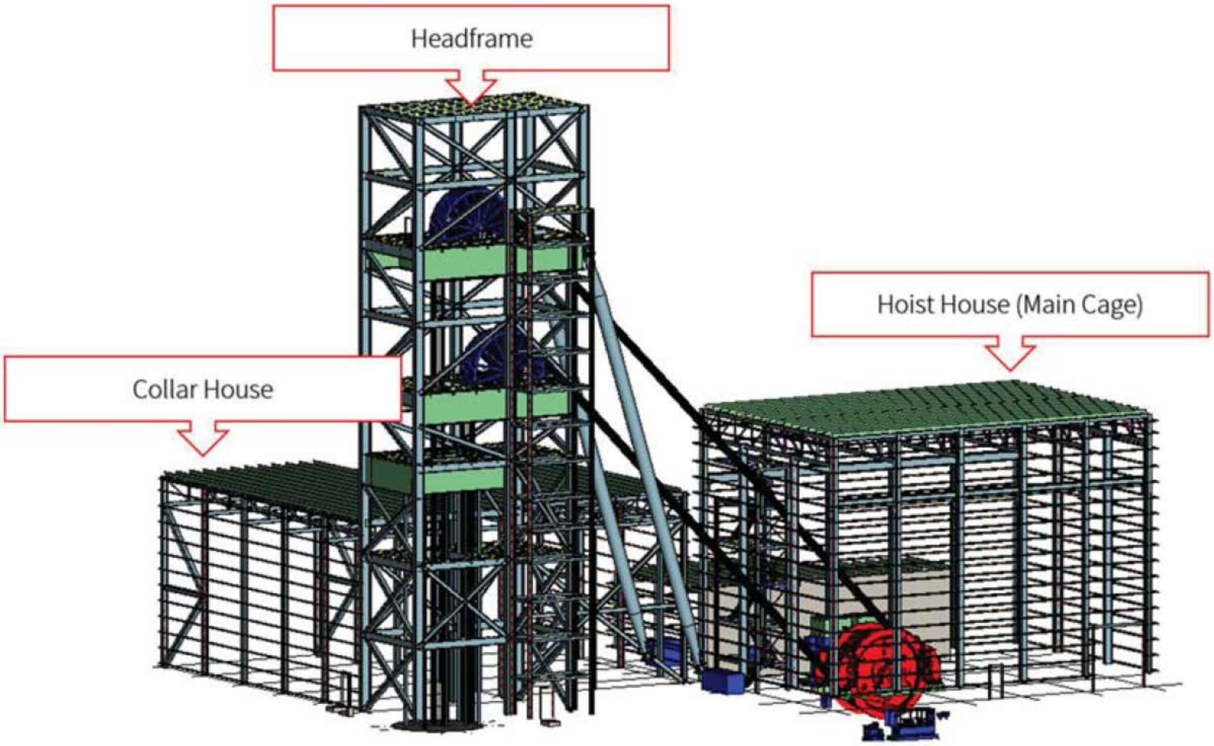


Figure 3-5: Main Shaft Surface Plant

The design work is conceptual for the purpose of supporting a Class 4 cost estimate. Future studies are required for the design of the shaft, headframe, and hoisting plant including hoist control room, internal outfitting of the surface plant, aging management, input from the shaft sinking contractor on permanent design, sinking configuration, and sinking methodology. Additionally, the design calculations for the hoisting system, headframe structure, shaft liner, and shaft steel will be revised as new information becomes available.

3.4.2 Sealing Materials Compaction Plant

The NWMO is advancing the design of the Sealing Materials Compaction Plant (SMCP) (Figure 3-6). SMCP operations will be required to produce repository sealing materials needed for the Engineered Barrier Systems (EBS) (e.g., bentonite blocks, granular bentonite gap fill material).

A 3-D model overview of the SMCP is shown in Figure 3-6, which is comprised of the following:

a) Storage of bentonite material.
b) Mixing, mould preparation and filling of the moulds with bentonite to produce highly compacted bentonite (HCB) products.
c) Cold isostatic press (CIP) compaction of the bentonite in the moulds to create HCB products.
d) Demoulding and machining of the HCB products to the required shapes for
e) placement underground.
f) Storage of the post machined HCB products.

a) Drying and processing (briquetting, crushing and screening) of bentonite into gap fill
g) materials (GFM).
h) Collection of residual bentonite or cuttings for re-use in the SMCP or disposal.
i) Placement of HCB buffer box components onto mobile equipment for transport to the Used Fuel Packaging Plant (UFPP); or to the Service Shaft for GFM or other HCB products.

Figure 3-6: Sealing Materials Compaction Plant

3.4.3 Concrete Batch Plant

Concrete Batch Plant operations will be required to produce concrete needed for underground construction (e.g., bulkheads, flooring, etc.).

The Concrete Batch Plant (CBP) is presented in the 3-D model overview shown in Figure 3-7, and the plant comprised of the following key areas:

1. Aggregate storage area comprised of in-floor heated storage domes for different aggregate materials.

2. Batching and mixing facility, comprised of aggregate feed bins, concrete mixer, binder storage silos and admixture addition systems.

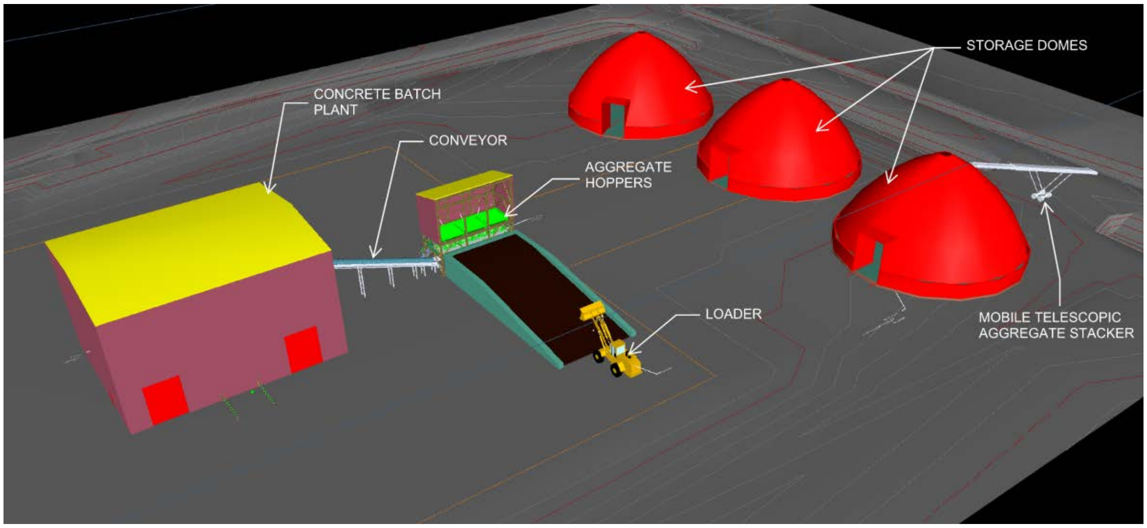


Figure 3-7: 3D Model Overview of the Concrete Batch Plant

3.4.4 Placement Room Shape Optimization

Stress and thermo-mechanical analyses were undertaken to establish an optimized placement room shape. Three initial shapes were compared:

(i) The base case rectangular room with square corners,
(ii) A room with round or chamfered corners, and
(iii) a placement room with an arched roof.

Based on the modelling, the placement room with an arched roof was chosen as the optimal shape. The optimal shape of the room is very similar to the previous base case. As shown in Figure 3-8, the width of the nominal arched room is the same as the nominal rectangular base case, with the maximum height of the arched room at 2.5 m compared to 2.4 m. To accommodate the top arched corners of the room, the corners of the upper Buffer Box will be chamfered to facilitate placement.

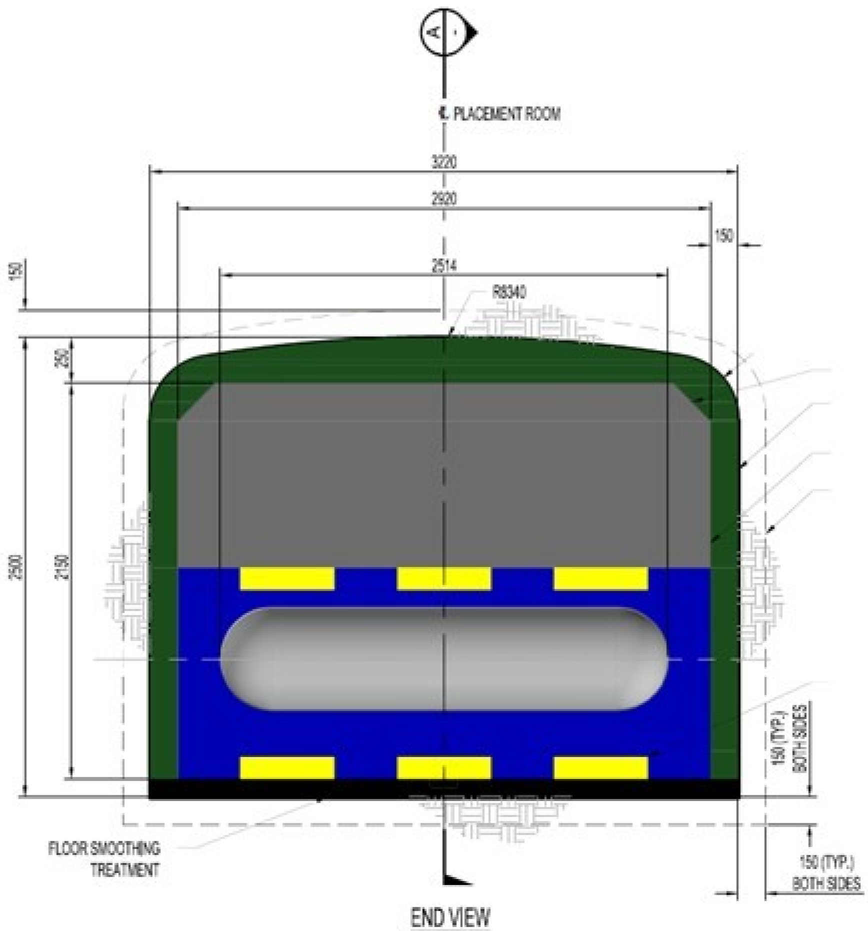


Figure 3-8: Arched Placement Room Cross Section

3.4.5 Decommissioning and Closure

A preliminary full-cycle decommissioning plan is being prepared in support of the latest cost and design update. The decommissioning and closure scope of services is divided into four key areas:

1. Removal of all above ground facilities (non-nuclear) and the UFPP (nuclear), and restoration of the site for the eventual post-closure future land use. It should be noted that the decommissioning of the used fuel packaging plant (UFPP) is planned for the early stages of the monitoring period.

2. Backfilling of all underground excavations and shafts.

3. Removal of Site utilities / services and water management infrastructure.

4. Restoration of the excavated rock management area (ERMA) to match the surrounding terrain.

3.4.6 Communication Systems

The purpose of this work was to document the design of the Communication Systems. The advancement of this work includes a description of all the systems and infrastructure that will facilitate the transfer of information and data across the surface area, underground area, Excavated Rock Management Areas (ERMA). These systems and infrastructure include:

a. Voice Communication System (VCS)
b. Emergency Telephone System (ETS)
c. Voice over Internet Protocol (VoIP) Telephone System
d. Ultra-High Frequency (UHF) Radio System
e. Closed Circuit Television (CCTV) System
f. Ethernet Cables
g. Fiber Optic Cables
h. Radio Frequency Identification (RFID) System
    - Card Readers for Access Control
    - Tags and Antennas for Location/Inventory Tracking
i. Wi-Fi System
j. Cellular Service
k. Server Rooms.

The Communication Systems were advanced to support an AACE Class 4 cost estimate and designed based on the expected needs of the DGR facility.

3.4.7 Surface Electrical Systems

The purpose of this work package was to document the latest design of the surface Electrical Distribution System. The advancement in the design provides a description of the Surface Electrical Distribution System. The Surface Electrical Distribution System will supply power to the loads within the surface facilities and processes. This system and infrastructure include:

a. High Voltage (HV) Substation
b. Medium Voltage (MV) (4.16 kV, 13.8 kV) Transformers
c. MV Switchgear
d. MV Emergency Generators
e. MV Power Cables
f. Electrical Rooms
g. Low Voltage (LV) transformers
h. Motor Control Centers (MCCs)
i. Variable Frequency Drives (VFDs)
j. Uninterruptible Power Supplies (UPSs)
k. Direct Current (DC) Power Supplies.

The design was advanced based on new information about on-site electrical power loads in major facilities and processes. Major electrical equipment was sized based on the regular and emergency electrical power demand for each facility. Electrical equipment was selected with considerations for redundancy, spare capacities, and preliminary short circuit calculation.

3.4.8 Subsurface Drainage & Dewatering

The design of the Subsurface drainage and dewatering system was advanced to support an AACE Class 4 cost estimate. The design was updated based on new information related to on-site water consumers and processes including mechanical equipment, piping, and underground infrastructure, and water recycling.

The subsurface drainage and dewatering system is comprised of the following systems:

1. Subsurface Dewatering System:

    a. Collection Sumps,
    b. Dewatering Reservoir and Main Pump Station,
    c. Inactive Drainage Pipelines.

2. Subsurface Water Recycling and Treatment System:

    a. Screening Station,
    b. Vertical Settlers,
    c. Decant and Filtrate Reservoir,
    d. Filter Presses,
    e. Water Filtration System.

3. Subsurface Service Water Distribution System:

    a. Service Water Reservoir and Pumps Stations,
    b. Service Water Pipelines,
    c. Booster Pump Stations,
    d. Pressure Regulating Valve Stations.

3.4.9 Underground Development Productivity Simulation

The purpose of this simulation work was to determine lateral development capacity and inform the construction schedules.

The simulation established a fleet size to meet the maximum lateral development rate required based on the previous construction plan. The number of workers in the labour pool will be adjusted to meet the specific placement rate for each panel.

3.4.10 Lateral Development Ground Support Design

This work estimated rock support requirements for the underground lateral development. These estimates were then used in the development of round cycle times (installation time) in the excavation.

The ground support estimates were based on the current understanding of the rock mass quality and conditions at the Revell site (WLON and Ignace area). The assessment is based on the empirical Support Design Chart by Grimstad and Barton based on estimates of Q (derived from RMR values) and an Equivalent Span Ratio (ESR), applicable to the facility and excavation type.

3.4.11 Placement Room Rejection Guideline

This work defined short term operational considerations and guidelines related to the placement of bentonite/buffer materials within placement rooms where flowing features are intersected. These guidelines were used to provide a set of assumptions related the repository design and layout for intersected inferred fracture zones, in the absence of detailed hydrogeological modelling at the time of design.

3.4.12 Subsurface Ventilation System

This work detailed the pre-feasibility design of the Subsurface Ventilation System. The design includes:

- Ventilation network.
- Placement arm construction ventilation.
- Placement room ventilation header.
- HEPA Filtration System (HFS).
- Primary and secondary fans and fan systems.
- Ventilation controls such as doors, walls, and regulators.

Several major design improvements to the design supporting the previous Lifecycle Cost Estimate (LCE) have been implemented, including:

a. The control and operation of the ventilation system has been simplified by replacing the underground booster fans with airflow regulators, eliminating the need to balance multiple fans in series parallel.

b. The use of airflow regulators, centrifugal exhaust fans with variable inlet flow control and variable speed, isolation and diversion control doors at placement arm intersections, and remote-controlled ventilation airlocks provides the flexibility to adjust the ventilation at any underground location from zero airflow to the entirety of the SVS airflow depending on the needs of an incident response.

c. The three HFS designs have been advanced to use commercially available bag-in/bag-out HEPA filter containment housings allowing filter replacement without exposing workers to contaminated filter media.

d. The use of installed spares in the primary fan stations and HFS allows regular fan and HEPA filter maintenance to occur without facility downtime by using duty cycling.

e. The process design of the HFS’s have also been modified to eliminate the reliance on HEPA fans, enabling faster engagement of the HFS’s with the use of centrifugal exhaust fans and rapid-acting control dampers, while also avoiding the need for “bubble-tight” dampers to protect against leakage of contaminated air.

3.4.13 Site Access Infrastructure and Primary Site Services

Design considerations for the overall Site Access Infrastructure and Primary Site Services were developed, including the design of two site access points from Highway 17 north of the site to the DGR facility. In addition, this advancement in design includes all the utilities required to provide services to the site, including natural gas, electrical power, and raw water tie-ins.

The following considerations were included in this work:

- Construction, Operations, Extended Monitoring, and Decommissioning phases of the DGR facility.
- Existing site access conditions based on the site survey provided by NWMO.
- Design criteria and design constraints and requirements.

3.4.14 Process Control System

Work was developed on the conceptual design of the Process Control System (PCS). This advancement provides a description of all the systems and infrastructure that will facilitate the control and monitoring of all applicable field devices on the surface area, the underground area, the Excavated Rock Management Areas (ERMA), and the ERMA access roads. These systems and infrastructure include:

- Programmable Logic Controller (PLC) and Remote Terminal Unit (RTU).
- Input/Output (I/O) modules.
- Annunciation panel (field devices).
- Human Machine Interface (HMI).
- Historian.
- Supervisory Control and Data Acquisition (SCADA).
- Servers.
- Control rooms.

The design of the PCS also includes implementing the necessary automation strategies to ensure efficient control and monitoring of the Instrumentation & Control (I&C) devices in the facility while covering the different levels of automation expected for the automated vehicles, mobile equipment, and applicable systems in the facility. The PCS was advanced to support an AACE Class 4 cost estimate and designed based on the expected needs of the DGR facility.

3.4.15 Physical Security System Design

Work was advanced on the conceptual design of the physical security measures for the DGR facility. This included as assessment of the security needs for the sites considering their location and the nature of the surrounding area, as well as regulatory requirements. Guidance from the International Atomic Energy Agency (IAEA) and regulations from Canadian Nuclear Safety Commission (CNSC) are used to shape the security framework for the facility. Along with other measures, barriers enclosing the facility are equipped with advanced sensing technology to deter, detect and delay potential intruders. A nuclear security force is equipped to respond to any threats. By applying security principles early in the design process, recognized security-by-design approaches can be used to maximize protection of the facility.

In addition, cyber security requirements for facility communications and control systems were considered. This information is used to help update the Lifecycle Cost Estimate for the DGR facility. Specific designs for security systems will be developed as the project progresses through regulatory approvals.

3.4.16 Environmental Protection and Monitoring System

Design considerations were developed for the engineering infrastructure required at the APM DGR facility and the Excavated Rock Management Area (ERMA) to support monitoring of effluent and environmental parameters throughout commissioning, operations, and decommissioning. This identified environmental media and associated sources for monitoring at a conceptual level such that the requirements for infrastructure needed to facilitate monitoring could be assessed; and provides design requirements for the infrastructure to support environmental monitoring including general equipment and access requirements. Environmental media included in the conceptual monitoring system include atmospheric, stormwater, service water and groundwater.

Monitoring airborne emissions could include exhaust air from the Exhaust Ventilation Shaft and the Main Shaft. This may include a Continuous Emissions Monitoring System (CEMS) for particulate matter or for airborne radionuclides. Ambient air quality monitoring may be used to capture any potential fugitive dust emissions of bentonite such as the Sealing Materials Compaction Plant, and dust produced from inside the Concrete Batch Plant or through material handling, waste rock handling, aggregate stockpiles, or unpaved roads. The site may be equipped with a meteorological station to monitor wind speed and direction, temperature and relative humidity, precipitation, and barometric pressure. Atmospheric monitoring could also include monitoring of noise.

Stormwater and service water effluent monitoring would include monitoring prior to discharge to the environment, to confirm that regulatory requirements have been met for treatment of stormwater. In addition, monitoring points may be placed to monitor effluent from the Service Water Settling Pond, DGR Dewatering Settling Pond and the Water Storage, Treatment and Distribution System at the sewage treatment plant.

Groundwater monitoring would be used to detect any effects of site operations on local groundwater, such as influence on local flow patterns and any effect from site operations on groundwater quality. The groundwater monitoring system would include upgradient and downgradient wells. The exact number and locations of wells will be established through the regulatory process.

Although specific monitoring requirements will be developed through the Impact Assessment and licensing process, this preliminary design information supports the Lifecycle Cost Estimate for the facility.

4 ENGINEERED BARRIER SYSTEM

The engineered barrier system (EBS) is a major component of the underground design. It includes the used fuel container (UFC) and buffer sealing systems. Work progressed on the UFC is discussed in Section 4.1 and 4.2. Work on copper durability and the buffer sealing system is presented in Section 4.3 and 4.3.3, respectively.

4.1 USED FUEL CONTAINER (UFC) REFERENCE DESIGN

The Mark II reference (conceptual) Used Fuel Container is shown in Figure 4-1, Figure 4-2, Figure 4-3. In 2024 efforts were focused primarily on the completion of the Conceptual Mechanical Design Report for the Mark II Used Fuel Container. In this report, the evaluation of the mechanical performance of the UFC based on the results of the design qualification program are presented. The design qualification considers a generic site and the conceptual design of the UFC, repository and its surface facilities, along with postulated service conditions and bounding conditions to assess safety objectives associated with the proposed pre-closure operations and post-closure conditions. This report has undergone extensive interdisciplinary review and will be issued in early 2025.

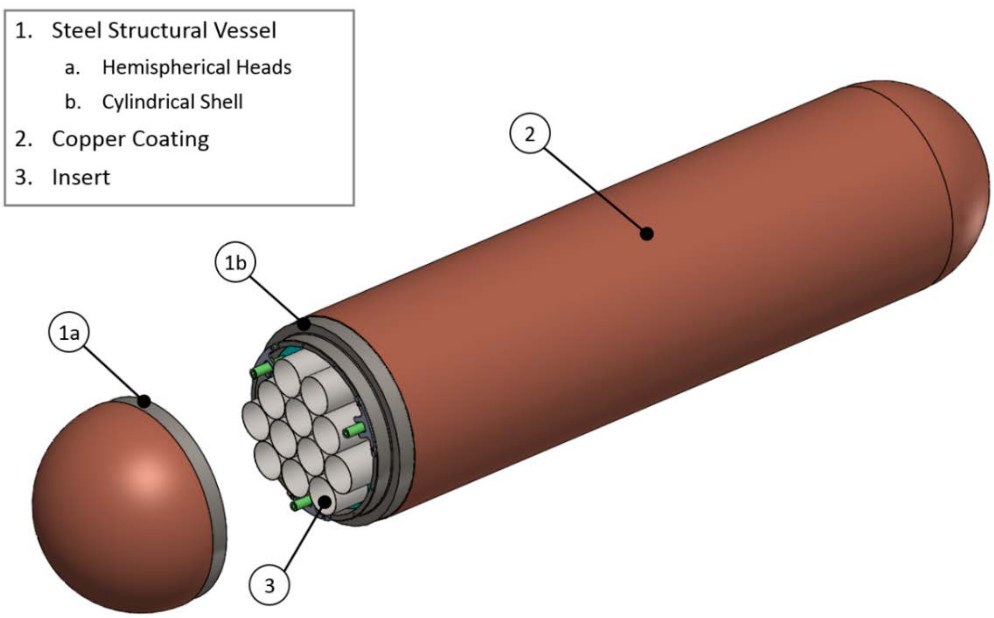


Figure 4-1: Illustration of the Mark II Used Fuel Container Reference Design

Figure 4-2: Mark II Used Fuel Container Reference Design Components (hemi-head, lower assembly and internal insert)

Figure 4-3: Assembled Mark II Used Fuel Container Reference Design

Also in 2024, progress continued on a program to develop supply chain capacity for the provision of electrodeposition copper coating services for the Mark II UFC. A program launched in 2023 to demonstrate BEP Surface Technologies Inc. ("BEP", Manchester, United Kingdom) processing method application to the Mark II Lower Assembly (LA) and Hemi-Head (HH) components was completed this year. In 2024, the NWMO received one copper coated LA and one copper coated HH from BEP. These components were subsequently finish machined and surface examined by visual and liquid penetrant (LP) methods with no defects observed. Subsequent inspection (Figure 4-4) using advanced non-destructive examination (NDE) techniques (phased array ultrasonic testing (PAUT), eddy current testing (ECT)) was performed by NWMO's NDE provider (Nucleom, Inc, Quebec City, Canada). The results indicate that all design requirements (bond, thickness) and quality characteristics (e.g., absence of volumetric and surface defects) were met with margin (e.g., no relevant indications or rejectable signals). This work, along with prior metallurgical qualification and demonstration, confirms that BEP is fully qualified to supply electrodeposition copper coating services to produce Mark II UFC shells, lower assemblies and hemi-head components.

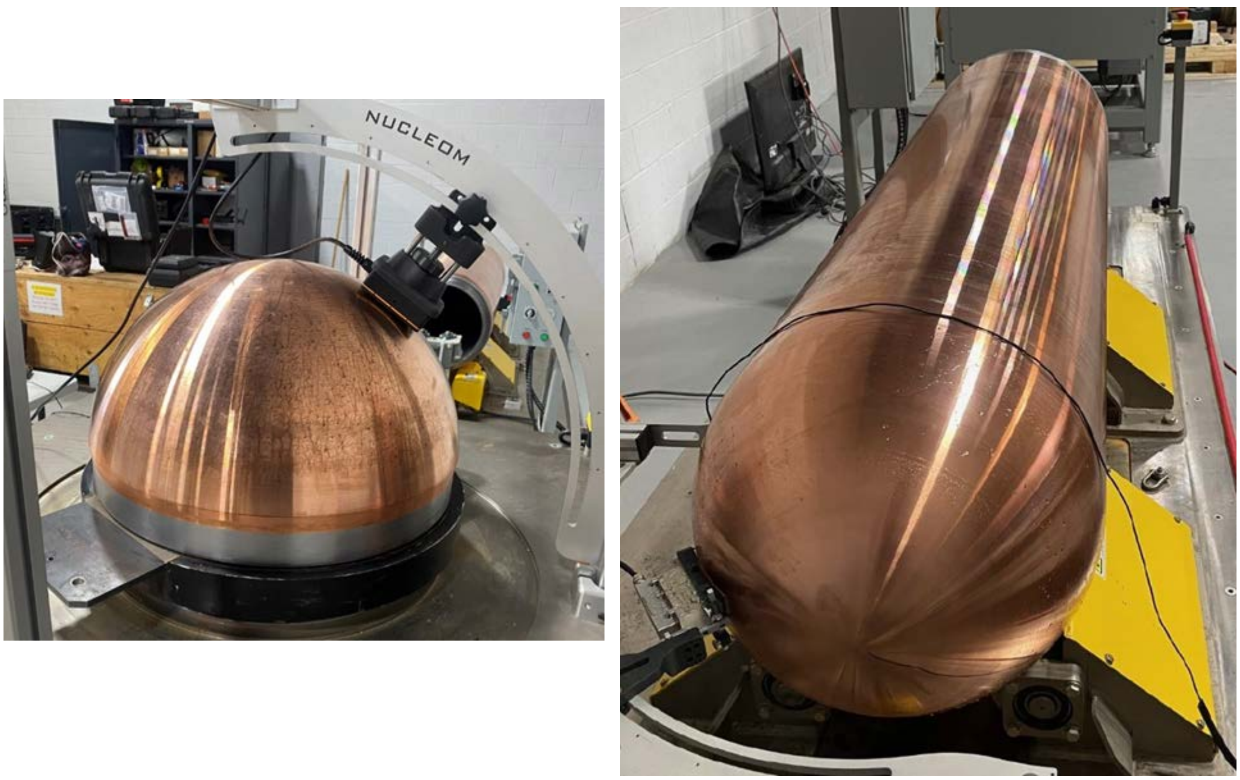


Figure 4-4: Non-Destructive Examination of Mark II UFC Hemi-head (left) and Lower Assembly (right) components copper coated by BEP Surface Technologies, Inc.

4.2 EBS INNOVATION INITIATIVE

With the announcement of Canadian utilities moving forward with the deployment of Small Modular Reactors, the NWMO, supported by an NRCan Grant, has commenced initial studies on disposal concepts for potential new high-level waste forms. While it is recognized that several SMR designs are being advanced in Canada, the GE-Hitachi BWRX-300 design has been selected by OPG for the Darlington's New Nuclear Project. Considering this waste form, the NWMO is studying potential UFC options and assessing impact on the EBS, UFPP and DGR design. One such design concept being considered is a large capacity UFC which may accommodate CANDU fuel bundles and SMR fuel (BWRX-300). This concept, illustrated in Figure 4-5, is called the Mark I Long.

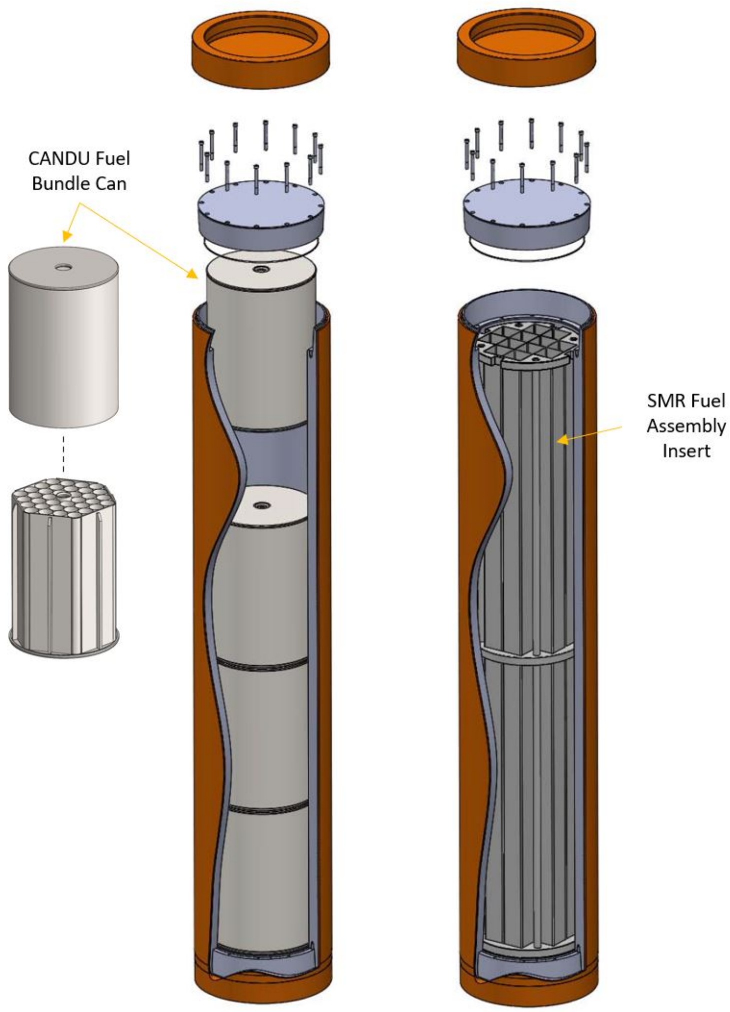


Figure 4-5: Illustration of the Mark I Long conceptual UFC for CANDU fuel (288 bundle capacity) and GE-Hitachi BWRX-300 SMR fuel (12 fuel assemblies).

The Mark I Long container is similar to the SKB/POSIVA KBS-3 canister design size/concept of a large ferrous structural vessel with a bolted steel flat lid and a welded copper overpack for corrosion protection. The NWMO is studying the feasibility of adapting copper coating technology developed for the Mark II Reference UFC to the Mark I Long design. Overall, the intent of the Mark I UFC concept is to leverage existing, demonstrated technology and processes that SKB/POSIVA have utilized for the KBS-3 including canister closure/inspection, UFPP design and transfer/emplacement which are viewed as being adaptable to the Mark I. The program is in the initial stages of pre-feasibility assessment.

4.3 COPPER DURABILITY

4.3.1 Used Fuel Container Corrosion Studies

4.3.1.1 Anoxic Corrosion of Copper

Following closure of the DGR, oxygen will be present for a short period of time. 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 groundwaters at either potential DGR host site 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 will ensure that movement of bisulfide will be limited to diffusion controlled mass transfer, the effects of bisulfide on the integrity of the UFC and the quantification of any such corrosion is important to understand. With respect to corrosion, the dominant groundwater anionic species in each case is chloride which is being studied at various concentrations in conjunction with bisulfide.

Collaborating studies are ongoing by the NWMO at CanmetMATERIALS (Hamilton, Canada) and Queen's University (Kingston, Canada). At CanmetMATERIALS, a number of anoxic cells were constructed and long-term corrosion studies initiated in some cases nearly a decade ago. In the absence of oxygen, any potential corrosion reactions will produce hydrogen gas as a product which can be captured, analyzed, and a copper corrosion rate calculated. The design of the corrosion cells also allows for the online spiking with gaseous hydrogen sulfide which dissolves into solution as very dilute bisulfide, thereby simulating the potential effects of microbiologically induced corrosion. An example of a long-term study (approx. 4 years) with relevant copper materials is illustrated in Figure 4-6. In general, cumulative hydrogen in the last year or so is stable and corrosion rates are declining.

In a more focused study, Queen's University in collaboration with CanmetMATERIALS looked at the effect of gaseous hydrogen sulfide on cold sprayed copper. Samples were exposed to 100 ppm of hydrogen sulfide in a nitrogen atmosphere within glass vials. The samples were exposed for either 2 or 6 months to obtain an understanding of the corrosion rate during the exposure. Some of the sample surfaces showed platelet like structures, which are believed to be a product of minor oxygen contamination (see Figure 4-7a). An SEM image of surface morphology of the platelets and corresponding XPS deconvoluted spectra are shown in Figure 4-7b, with the dark blue representing the sulfur-sulfur bonding and the green matching with copper (I) sulfide. XPS also reveals that the platelet structures are polysulfide.

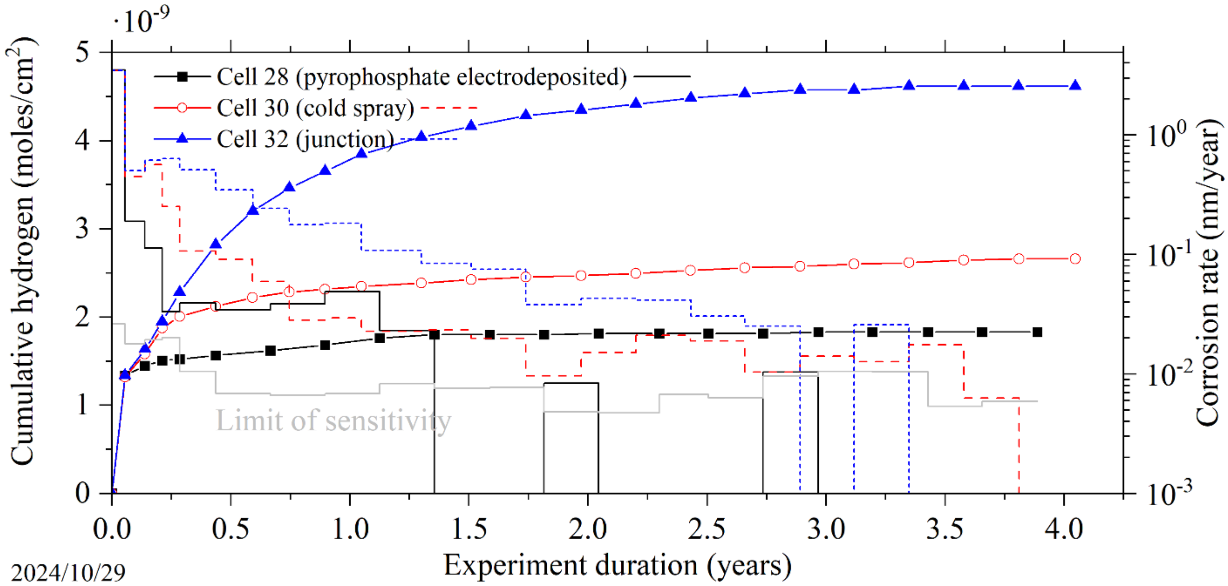
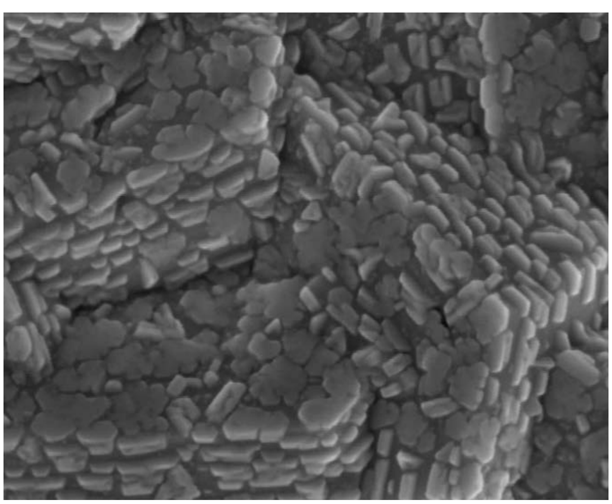
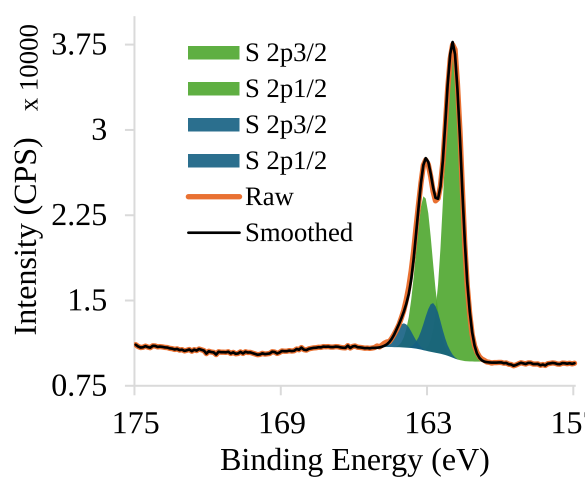


Figure 4-6: Long term corrosion experiments for repository copper materials in simulated waters found in sedimentary host rocks (solid lines for cumulative hydrogen and dashed lines for the corrosion rate): Cell 28 – bulk copper coating on UFC components using electrodeposition, Cell 30 – cold sprayed copper coating at closure weld zone, and Cell 32 – junction where electrodeposited and cold sprayed copper meet to complete the coating.



(a)



(b)

Figure 4-7: (a) SEM image of platelet formation of cuprous sulfide and (b) corresponding XPS spectra of the S 2p peaks on the sample surface.

Future work will include using a focused ion beam (FIB)-SEM for cross sectional imaging to observe the structure of the film through its thickness which might offer insight into the growth kinetics and passivity, as this may lead to some non-uniform corrosion). Additionally, angle-dependent X-ray diffraction characterization will allow for the determination of sulfide film orientation as a function of depth to investigate any preferential growth direction. Electrodeposited copper will also eventually be subjected to the same analyses.

4.3.1.2 Microbiologically Influenced Corrosion

As described in Section 4.3.1.1, the repository environment is anticipated to evolve from early oxic conditions to later anoxic conditions. Under anoxic conditions, microbiologically influenced corrosion (MIC) could occur, where sulfate-reducing bacteria acting in remote areas within the host rock produce bisulfide (HS^-) that can transport through compacted bentonite (HCB) and corrode the copper barrier. This is an interdisciplinary study that includes investigation of processes such as microbial activity, species transport through the HCB as well as corrosion dynamics. An extensive research program funded by Ontario Research Fund (ORF) has been investigating these processes in detail since 2018. The update on the microbiology component is reported below in Section 4.3.2.

Due to the low permeability of bentonite, bisulfide transport is diffusion controlled and can be affected by geochemical reactions or sorption mechanisms. Quantifying HS^- transport through HCB using diffusion experiments under a range of anticipated DGR conditions (e.g., temperature and ionic concentration) as well as HCB densities has been completed. The results indicate that HS^- does interact with bentonite to affect the diffusion-controlled transport processes (Chowdhury et al. 2024, Rashwan et al. 2023). As it was previously postulated that sorption (via adsorption and geochemical reactions) onto bentonite will reduce HS^- transport and minimize the risk of copper corrosion, a systematic study was concluded in 2024 in laboratory batch experiments investigating HS^- sorption onto bentonite slurries as a function of temperature (10-40˚C), pH (9-11), and ionic strength (0.01 M-1 M NaCl). These conditions were aimed to reflect the range of possible DGR geochemical conditions and the experimental results showed that HS^- sorption onto bentonite increased with increasing temperature but decreased with increasing pH and ionic strength (Papry et al. 2023).

To complement the experimental study, a thermodynamic-based sorption model was also developed in PREEQC assuming that sorption was driven by three key processes: (i) redox reaction with the structural Fe^{3+} sites, (ii) surface precipitation as FeS (mackinawite), and (iii) surface complexation reactions with surface hydroxyl group (OH) at the edge sites of montmorillonite. The model successfully described the main experimental trends and provided valuable insights into the relative contribution of these processes to the total HS^- sorption mechanism. The detailed manuscript is expected to be published in 2025.

4.3.1.3 Corrosion of Copper in Radiolytic Environment

The copper coated UFC will be exposed to a continuous flux of γ-radiation emitted from within as a result of 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. There have been a number of approaches to predicting the radiation induced corrosion of UFC and of the spent fuel itself (Eriksen et al. 2012). These approaches can be broadly classified as being either empirical or deterministic. Deterministic models are based on a prediction of the yield of radiolytic oxidants (and reductants) using some form of bulk radiolysis model.

Deterministic models can be further classified as either coupled or uncoupled, with the primary distinction being the degree of coupling between the interfacial electrochemical processes and bulk radiolysis model. Uncoupled models are the more common, for which it is assumed that the yield of radiolytic oxidants is independent on the rate at which they are consumed in the interfacial corrosion reaction.

NWMO has recently been advancing several models (King and Behazin 2021, Behazin et al. 2023) and is currently in the process of converting existing models and developing new coupled models using the commercial software package COMSOL Multiphysics (see Section 4.4.2.1). The code is designated the Copper Corrosion Model for Radiation-induced Corrosion (CCM-RIC) to predict the extent of radiation induced corrosion (RIC) by coupling a radiolysis model to the interfacial electrochemical reactions on the container surface. An important component of the overall model is a water radiolysis model to predict the time-dependent concentration of oxidizing and reducing radiolysis products as a function of decaying dose rate. Various simulations have been validated against experimental measurements of the concentrations of dissolved and gaseous radiolysis products. The results from these experiments have been compared with predictions from corresponding radiolysis models, including the effects of the partitioning of gaseous species (O_2 and H_2) at the gas-solution interface. In addition to validation and verification steps for the water radiolysis model, progress has been made in understanding the effect of chloride and bromide (as groundwater constituents) on the time-dependent concentrations of water radiolysis products as a function of dose rate. The first phase of the work was completed in 2023 (Behazin et al., 2023, Briggs et al., 2023) and phase 2 work from 2024 is expected to be published in 2025.

In addition to NWMO’s modelling efforts, experimental work is underway as part of Canadian academic programs as well as international consortium work packages (ConCorD) to provide empirical data for model validation and also to answer the remaining questions in this area. Most notably, the ConCorD work package as part of European Joint Program on Radioactive Waste Management (EURAD) included a series of irradiation experiments conducted by Amentum at Harwell Irradiation Facility to evaluate the corrosion behaviour of candidate container materials under anticipated DGR conditions as well as conditions that extend beyond those expected, e.g. higher dose rates. The outcome of this project that has been partly published (Hesketh et. al. 2024) aims to answer a long-standing question regarding whether radiation dose rate is the key factor in radiation induced corrosion allowance or the total dose. Additional analysis is underway to accurately measure the hydrogen in the irradiated copper samples to better understand if irradiation does lead to H absorption and while unlikely, whether there will be an adverse effect on the UFC coating. This work package is expected to be completed by the end of 2025.

4.3.1.4 Localized Corrosion of Copper

In principle, localized corrosion is the result of the spatial separation of anodic and cathodic processes, typically as a result of one of two main mechanisms:

- Localized breakdown of a passive film that exposes the underlying metal to solution. In this case, the anodic process is the oxidation of the metal, while the reduction process (typically of water or oxygen) occurs on the metal oxide.
- The presence of a geometrical discontinuity or occluded region that restricts the transport of reactants to, or of corrosion products away from, the anodic and/or cathodic sites.

Under anoxic conditions, the flux of sulfide to the UFC surface is extremely low due to the small amount of sulfide produced by microbial activity outside of EBS and its low diffusivity in the 10's cm of compacted bentonite (King et al. 2017, Salonen et al. 2021). As a result, the Cu_2S films formed have been shown to be porous and non-protective, rather than being passive and susceptible to localized film breakdown.

Extensive research to date has demonstrated that localized "pitting" corrosion under repository conditions is extremely unlikely. In the relatively brief oxic environments that exist post-closure, oxygen will be consumed well before the bentonite saturates, while in anoxic conditions the nature of the film prevents passivation or the development of physical barriers of corrosion products (Chen et al. 2014, 2017; Guo et al. 2019, 2020; Martino et al. 2014, 2017, 2019a,b; Smith et al. 2007). Accordingly, studies now focus on localized corrosion in unsaturated conditions, a process that is likely to be much less damaging, owing to the need for water to support sustained corrosion.

Studies that are underway include exposing the copper samples to a range of anticipated conditions under oxic phase, including radiation, different relative humidity and salt contaminations (Situm et al., 2024). As part of a separate project, localized electrochemical reactivity, and localized corrosion regions on Cu coatings are being assessed using scanning electrochemical probe microscopy (SEPM) to gain insight on how microstructural difference could impact local reactivity of copper (Saxena et al. 2024). From these experimental studies, it is clear that any localized corrosion damage will be minimal, consistent with the expectations of a few tens of microns previously published (Hall et al 2021).

In addition to experimental research, a mechanistic model of pitting is being developed. Specifically, localized corrosion under a droplet during the early oxic 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 2024. During this phase, when bentonite is unsaturated 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 is also being conducted at the University of Florida to develop a finite-element model with the means to predict, mechanistically, the rate and extend of localized damage due to copper corrosion has been published in 2024 (You et al., 2024). Results to date show an almost uniform depth of corrosion in an Evans droplet for DGR environmental conditions: corrosion does not localize. This work demonstrates the droplet localized corrosion mechanism is not conducive to the creations of deep copper pits.

4.3.2 Microbial Studies

Following closure of the DGR, rapid depletion of trapped oxygen and eventual saturation of the bentonite by groundwater the primary long-term threat to container integrity is via hydrogen sulfide. Since the host rock at DGR depth does not naturally contain hydrogen sulfide in the groundwater, the only potential source of these species is through microbiological activity. The microorganisms responsible for sulfide production, called sulfate-reducing bacteria (SRB) will only be viable should all of the environmental conditions allow it. Close to the container, dense bentonite is required to ensure that SRB will not be afforded sufficient food, water or space to grow. Through a combination of HCB and Gap Fill Material (GFM), nominal average dry density of bentonite is expected to exceed 1.6 g/cm^3. However, as HCB has a higher dry density (i.e. > 1.7 g/cm^3) than GFM (>1.4 g/cm^3) it is likely that there will be some heterogeneity of the density.

Accordingly, work is being conducted to explore the viability of microorganisms in a range of dry densities to fully understand the nature of the microbes and their ability to grow in bentonite clay. HCB in particular has been extensively examined in 2024.

Significant effort has previously been dedicated recently to optimizing the extraction and characterization of deoxyribonucleic acids (DNA) held within the bentonite since this genetic material is not abundant (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). In addition, efforts to culture microbial species from bentonite have been ongoing, concurrent with the development of DNA extraction methods.

To supplement the in-situ work being performed in underground laboratories, pressure vessels have also been designed, fabricated, and commissioned to perform many ex-situ experiments at Western University as shown in Figure 4-8 (a) and Figure 4-8(b). Beginning in 2022, scoping experiments were conducted where bentonite samples (powdered and GFM) ranging from dry densities from 1.1 to 1.6 g/cm^3 were saturated with water for up to 18 months. The first cells which were under oxic conditions were previously disassembled and analyzed for microbiological taxonomy and cell abundance.

A)

B)

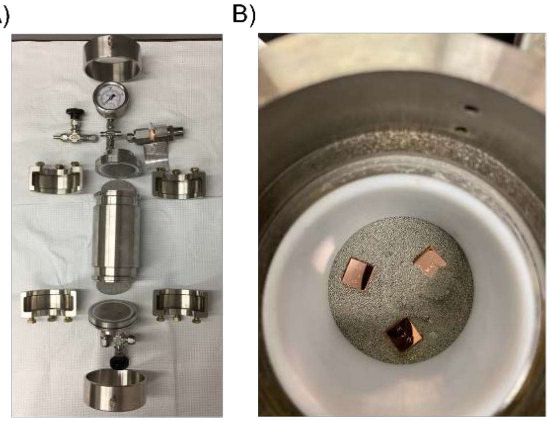
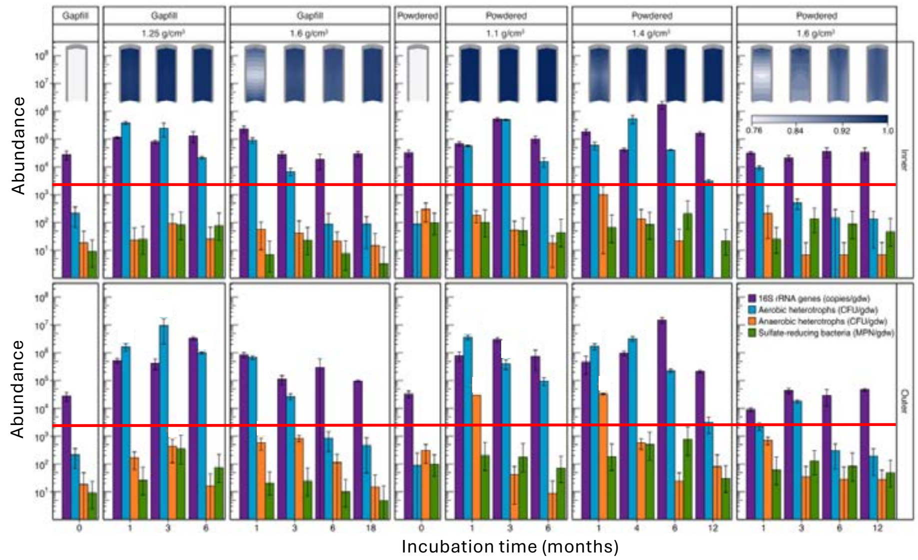


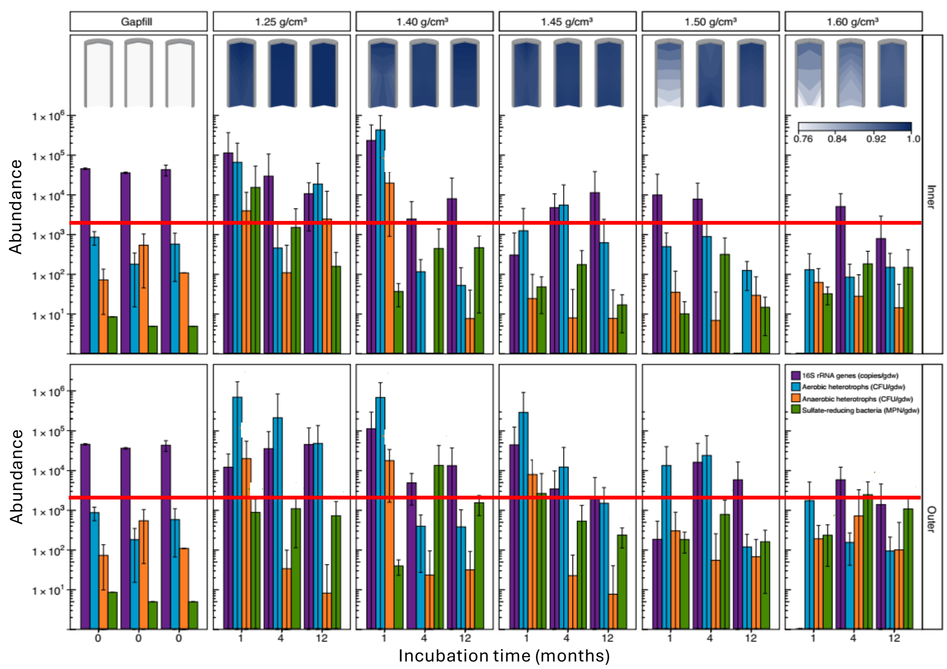
Figure 4-8: (a) Pressure vessel for ex-situ microbiological and corrosion analyses; (b) Pressure cell inside showing copper coupons and bentonite

After completion of the oxic pressure cell tests, these pressure cells were used to conduct the anoxic pressure cell tests to assess the minimum dry density required to suppress microbial growth in anoxic conditions, when SRB are most likely to grow.

For the anoxic pressure cell tests, the same GFM was used and compacted at dry densities from 1.25 to 1.60 g/cm^3 in duplicate. Prior to assembly, the GFM was transported to an anaerobic chamber for at least 48 hours before pressure cell assembly to allow for the removal of any oxygen remaining in the bentonite. Pressure cells were assembled and disassembled in an anaerobic chamber. All cultivation was also done in the anaerobic chamber.



(a) Oxic pressure cell test results



(b) Anoxic pressure cell test results

Figure 4-9: Abundance of 16S rRNA gene copies/gdw, aerobic and anaerobic heterotroph CFU/gdw, and SRB MPN/gdw for bentonite samples under oxic and anoxic conditions (after Beaver et al. (2024) and Beaver (2024)).

Figure 4-9 (a) shows culturing (and RNA) results obtained from the pressure cell tests under both oxic and anoxic conditions. Note that the abundances (or the RNA) of cultured microorganisms are plotted on the y-axis with the incubation time on the x-axis. Time 0 indicates the as-received powdered bentonite. The types of microorganisms measured are indicated by the colour of each bar, and bentonite dry density of each sample is indicated on the top of the figure. The contour plots (top of the figure) represent the water activity throughout the pressure cell. Error bars represent the standard deviation of replicates. In addition, the samples were selected from either immediately adjacent to the pressure vessel wall (outer) and from the centre of the pressure vessel (inner).

It is noted that colony forming unit (CFU)/g is abundance estimate using plate counts, where the standard countable range for plate counts is 20 - 200 colonies/plate. Counts of fewer than 20 are considered statistically insignificant. Therefore, the threshold value of 2000 CFU/g (shown as red lines) is based on 20 colonies detected in 0.01 g of bentonite for a 1:10 dilution. Below this threshold, estimates using the most probably number (MPN) method were calculated for abundance estimates of culturable SRB; the lowest value calculated was <1.8 cells/g.

As can be observed, SRB (green bars) and anaerobic heterophiles (orange bars) were generally not culturable in oxic conditions from either the inner or outer samples. SRB in particular were non-competitive, even for low densities, which did show growth of aerobic heterophiles (blue bars).

Within the outer bentonite samples (lower plots), aerobic heterophiles showed growth even at high dry densities. This was attributed to growth during initial saturation, when the outer layer of bentonite can initially swell as it wets, lowering its equivalent dry density. The lower density permits a short period of favourable growth conditions before wetting of the inner bentonite core results in compaction of the outside layer and suppression of growth. Inner bentonite (upper plots) showed no growth at densities >1.45 g/cm^3. Time-dependent effects can be observed within individual data sets by comparing 1-12 or 18 month data.

Figure 4-9 (b) shows the abundances of culturable microorganisms in the granular bentonite (GFM) under anoxic conditions. Similar to the results obtained from the oxic pressure cell tests, the abundance of culturable microorganisms increases beyond the measured abundances in the granular bentonite after starting saturation. Bentonite samples with dry densities higher than 1.40 g/cm^3 show that the abundances of culturable microorganisms remain below the threshold value after 12 months. In addition, both inner and outer regions indicate a decreasing trend of the SRB abundances with time, reaching very low abundance values below the threshold limit.

Microbial growth in bentonite under oxic and anoxic conditions is compared in this section. The test results clearly indicate suppression of microbial growth by bentonite with a dry density higher than 1.4 g/cm^3. The microbial study with these pressure cells is continuing to collect more long-term data that allows for statistical analysis of the granular bentonite under anoxic conditions, in order to build more confidence in the use of bentonite as a component of the engineered barrier system and ensure the long-term sustainability and safety of Canada’s DGR.

4.3.2.1 Mont Terri HT (Hydrogen Transfer) Project

The Hydrogen Transfer project is a gas circulation experiment which occurs at the Mont Terri underground rock laboratory in Switzerland. This is an *in-situ* experiment with the aim of evaluating hydrogen consumption processes in a borehole and determining the role of microbial activity on these processes in an Opalinus Clay environment. Hydrogen is injected near the borehole mouth continuously and the seepage 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 published in 2022 outlines the numerical modelling efforts that have occurred to better understand the data acquired on the fate of hydrogen within the experiment (Damiani et al. 2022). Currently, the modelling 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 a DGR, the presence of bentonite is expected to supress any such behaviour of sulfate-reducing bacteria.

The NWMO will decide in 2025 in which experiments to remain as an active partner at the Mont Terri URL (in sedimentary rock), given the site selection decision.

4.3.3 Environmentally Assisted Cracking of Copper

The predominant mechanical forces that will affect the copper-coated used fuel container (UFC) within a deep geological repository (DGR) are compressive in nature, owing to the combination of the swelling of bentonite buffer, the hydrostatic head from the emplacement at depth below the water table and periodic glaciation at the surface, above a DGR. However, during the lifetime of a DGR, there are periods of time during which stresses may not be isostatic, owing to the slow process of buffer wetting, and hence non-uniform swelling that would result from this process. Depending on the shape of the vessel itself, this type of uneven loading may result in non-uniform stress application to the container. In fact, the vessel shape may see uneven stresses even during purely isostatic loading, as sharp corners are known to accumulate significant localized stress, while arched shapes are less likely to see stress accumulations.

Accordingly, it is possible that some tensile force will be imposed on the copper surface during the repository lifetime. Depending on the condition of the copper, the (external) environment surrounding the copper coating and the magnitude of the tensile stress, it is theoretically possible that tensile forces may contribute to cracking of the copper.

To address this, a new 5-year program was launched in late 2024 with Queen’s University with a primary focus on understanding the nanoscale mechanisms and precursors to stress corrosion cracking (SCC) of copper in nitrite and sulfide solutions. Specific to this subject, the program is divided into the following tasks:

1. Mechanistic understanding of intergranular (IG) and transgranular (TG) SCC in aerated nitrite solutions and defining thresholds

2. Sulfide-SCC of copper variants relevant to Canada and the effects of chloride

Additionally, the program will look at related factors such as the effect of hydrogen and other impurities on copper embrittlement under relevant conditions.

4.3.4 Field Retrievals and Deployments

To complement the work in the Engineered Barrier Science group performed in a laboratory setting, field experiments were initiated to elucidate the fundamental processes related to copper and bentonite integrity. Thus, efforts have been directed to evaluating the synergistic behaviour of copper embedded in bentonite deployed in a DGR-like environment. This work utilizes so-called “module experiments” adapted from designs created by Nagra, the Swiss nuclear waste management organization.

4.3.4.1 Borehole Module Experiment

As reported previously, in September 2021, six modules were deployed in the WLON-Ignace area in borehole IG_BH02 by Solexperts AG of Switzerland (see Figure 4-10). Modules contained UFC materials encased in compacted bentonite and were placed at a depth of approximately 300 m below surface, where it is anoxic and fully saturated. In October 2023, two modules were exchanged for new ones.

Each module retrieved in 2023 contained cold sprayed, electrodeposited and wrought copper (see Figure 4-11) samples. One module had a target bentonite clay density of 1.25 g/cm^3 density while the other was at 1.50 g/cm^3.

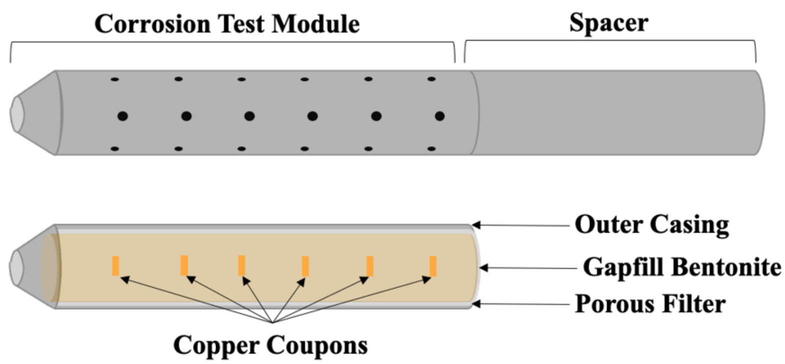


Figure 4-10: Schematic of borehole module containing two of each copper type (cold sprayed, electrodeposited and wrought) for a total of six samples.

In 2024 the retrieved samples were analyzed and corrosion products were examined to determine their composition. In addition, the two-year corrosion rate was calculated based on mass loss after removing corrosion products. Given both the very small weight changes observe the challenge in removing the corrosion product without removing the metal in weight loss measurements.

Example optical and SEM micrographs, which show very modest damage for samples embedded in 1.50 g/cm^3 of bentonite clay density, are shown in Figure 4-11 (from top, wrought, cold-sprayed and electrodeposited coppers). From further analysis, Figure 4-12a shows the corrosion product composition for a selection of copper materials, while Figure 4-11b shows the calculated corrosion rates for cold sprayed and electrodeposited copper.

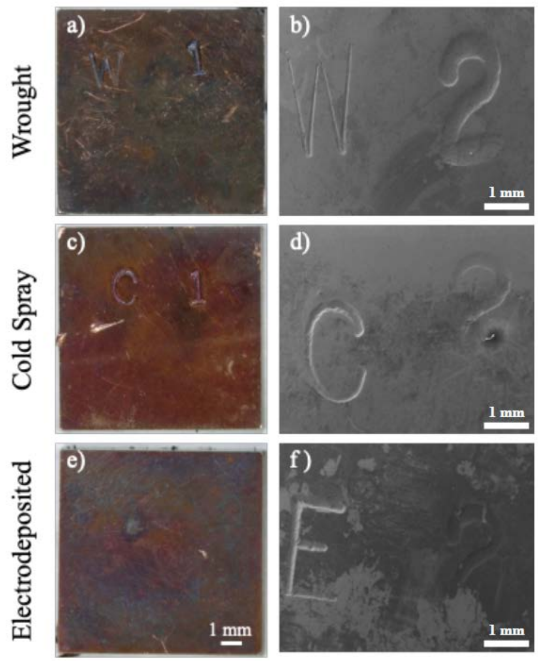


Figure 4-11: Optical and SEM images showing non-uniform corrosion across all three different copper type surfaces when embedded in 1.500 g/cm³ density bentonite clay at a depth of 300 m after two years.

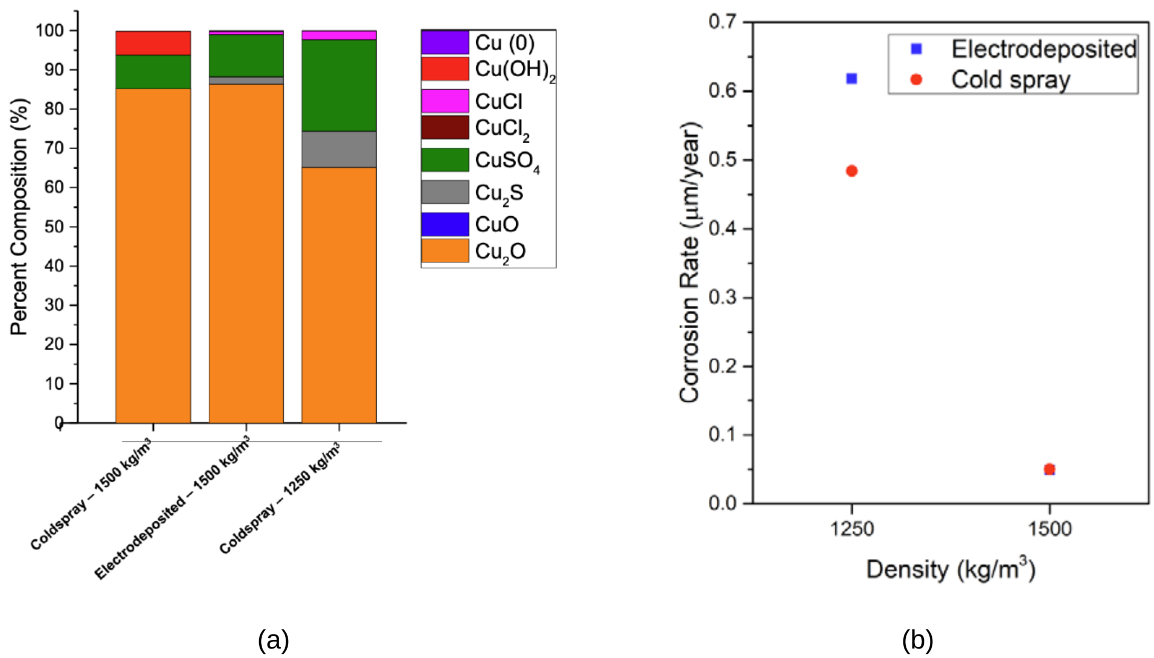


Figure 4-12: (a) Corrosion product composition determined by XPS for selected specimens and (b) average corrosion rates of copper specimens from borehole exposure after approximately two years.

In all cases, the (average) corrosion rate calculated was low (i.e., < 1 µm/a), particularly in high density bentonite, where it was more than an order of magnitude below that (i.e., < 0.1 µm/a). Observed damage is consistent with exposure to oxygen during module assembly and/or transfer to the borehole. Further analysis of these specimens is ongoing, as well as assessment of the bentonite clay for microbial species, to better understand the applicable mechanisms of corrosion.

4.4 PLACEMENT ROOM SEALS AND OTHERS

4.4.1 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. The GAST (Gas permeable Seal Test) project was initiated by Nagra at the Grimsel Test Site, Switzerland in late 2010, with the main purpose to demonstrate the feasibility of the Engineered Gas Transport System (EGTS) at full scale. The EGTS 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 a partner of the GAST project from the very beginning.

In 2024, Phase 3 of the GAST project was successfully completed and this is considered a major milestone for the GAST project. Below is a brief summary of the GAST project since its inception.

Initially GAST was planned as a single-phase test; two new phases (Phase 2 and Phase 3) were added until the gas flow test (GFT) could be successfully performed (Figure 4-13).

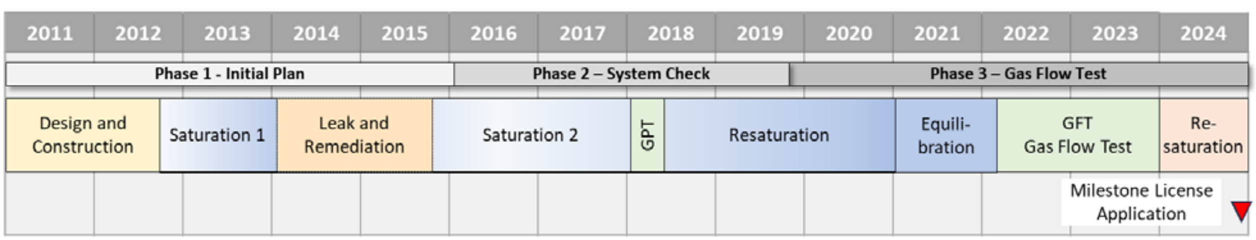


Figure 4-13: Timeline of the GAST Project until 2024

The first three years of the field test proceeded as planned with the major deviation that the saturation of the experiment was significantly slower than the model predictions. Additionally, a major leak event occurred in 2014 that required significant time and effort to repair. Hence, Phase 2 was required to continue the experiment, within which the saturation was resumed, and a series of gas property tests (GPT) were performed. The objective of the GPT was to determine the effective functioning of the system and to prepare equipment for the gas flow test (GFT). Following the GPT, the system was re-saturated and pressurized up to about 2.0 MPa. In Phase 3, preparation and execution of the GFT with subsequent data evaluation and reporting were successfully implemented as evidenced by:

- Two high-recovery gas tracer tests were successfully performed over 1.5 years in Phase 3.
- End-to-end gas flow through the sand/bentonite seal was unambiguously detected.

- A high-quality dataset was obtained for further interpretation and modelling.

The key findings of the GAST project were part of the documentation for Nagra's license application in November 2024.

4.4.2 DECOVALEX Modelling

4.4.2.1 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 Full-scale Emplacement Experiment (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 (Müller, 2017). 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.

The FE experiment at the Mont Terri Underground Rock Laboratory was designed to replicate the emplacement tunnel of Nagra's reference repository design at 1:1 scale (Figure 4-14) (Müller, 2017). One of the objectives of the experiment is to investigate used fuel repository-induced THM coupled effects of the host rock at full scale and to validate existing coupled THM models (Müller, 2017; Nagra 2019).

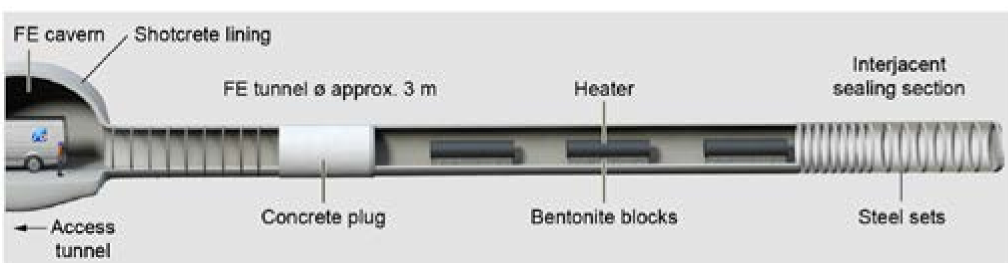


Figure 4-14: Diagram showing the layout of the FE experiment at the Mont Terri rock laboratory (From Müller et al. (2017))

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

In the period of 2020-2023, ten modelling teams have performed the 2D thermal, coupled TH and coupled THM modelling FE experiment using different numerical modelling programs and the results were compared among different teams and with experimental data. All of the models are able to reproduce the correct range of behaviour for temperature and pressure evolution in the Opalinus Clay, but it has been challenging to match closely. Efforts were documented in the final DECOVALEX report (Graupner et al. 2024).

The NWMO performed all of these modelling and obtained results which well aligned with most of international modelling teams results and with measurements (Guo and Briggs, 2024). NWMO modelling work included a sensitivity study that examined the influence of assumptions regarding the heater representation in the model (geometry, thermal properties, application of the heat load) and proved that these assumptions had a significant influence on the heater temperatures and the temperature of the placement tunnel sealing material but not in the Opalinus clay (OPA) rock surrounding the placement tunnel. A second sensitivity study proved that the initial pore water pressure in the Opalinus clay had a significant influence on the pressure accumulation over time. A third study confirmed that using as-placed (unsaturated) thermal conductivity for the bentonite sealing material can give conservative thermal results.

4.4.2.2 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-2023/2024 involves comparison of the models and methods used in post-closure performance assessment of deep geologic repositories.

In 2023, Task F was completed including benchmarking of the various software programs and performance assessment tools used in Task F against hydrogeological flow and a transport problem with known analytical solutions. The NWMO performed these benchmarks with the Integrated System Model (see Section 6.4.3.2.1) and its constituent codes COMSOL and HydroGeoSphere.

At present the generic crystalline rock model site consists of a rectangular domain with a topographic high as one end of the site. The site rock and fracture characteristics are based on the Posiva characterization of Onkalo site, and the hypothetical repository is based on the KBS-3 vertical in-floor disposal concept. In 2023, Task F participants finalized their respective modelling activities including comparing results of the benchmark and generic crystalline site assessment. The DECOVALEX Task F final Report was published in 2024.

4.4.3 Tunnel Seal Properties

The current tunnel seal concept includes two bentonite-based sealing materials, bentonite-aggregate (B-A) mixture (previously called dense backfill (DBF)) and gap fill material (GFM). B-A mixture is required to fill large horizontal openings (e.g., tunnels and non-placement rooms) located in working level(s) of the outside placement rooms. Since the geometry in the DGR will limit the ability to compact the B-A mixture particularly in the areas close to tunnel walls and roof, it is assumed that B-A mixture will be installed in horizontal layers until it has reached a level where compaction is no longer possible. The remaining volume between the B-A mixture and the roof will be filled with GFM.

The basic swelling pressure and hydraulic conductivity requirements for the B-A mixture are as follows:

1. Swelling pressure (Ps), or pressure at contact between B-A mixture and its confinement (rock or concrete structures) should be >100 kPa),

2. Hydraulic conductivity (k) needs to be <10^{-10} m/s,

3. Sedimentary DGR will require use of limestone aggregate and functioning of B-A mixture at high groundwater TDS (e.g., SR-290),

4. Crystalline DGR will require use of granitic aggregate and assumes the presence of a low TDS groundwater (e.g., CR10), and

5. When estimating Ps and k, it assumed that the Engineered Materials and Disposal Design (EMDD) concept is applicable to B-A mixture.

In 2024, the NWMO optimized the B-A mixture for both reference groundwaters to meet interface contact pressure design requirements and characterized the components of the B-A mixture specified for compaction properties.

Based on the compaction test results, new B-A mixture ratios (bentonite content up to 60%) at various dry densities were prepared, and the laboratory testing of these mixtures is conducted to meet the design requirements (swelling pressure >100 kPa and hydraulic conductivity <10^{-10} m/s).

4.4.4 Bentonite-Low Heat High Performance Concrete

The NWMO reference concrete is Low Heat High Performance Concrete (LHHPC). The LHHPC mixture was optimized, and its properties were measured from 2019 to 2021. Details of the optimization and material properties are provided in NWMO-TR-2021-20 (NWMO 2021a).

Upon completion of the LHHPC testing program, the NWMO initiated a new testing program in 2022 to assess the long-term interaction between the bentonite-based materials and LHHPC. As part of the NWMO placement concept, the LHHPC will be in contact with the bentonite-based materials and begin to evolve as soon as it is saturated with groundwater from the geological formation. That will likely modify the bentonite’s geochemistry, mineralogy and texture near the concrete/bentonite interface. Consequently, this modification will affect the performance of the bentonite-based materials in the placement room.

(a) Test cells with water tanks

(b) LHHPC in the cell

(c) Compacted bentonite-LHHPC in the cell

Final setup

Figure 4-15: Bentonite-LHHPC Test Cell Setup

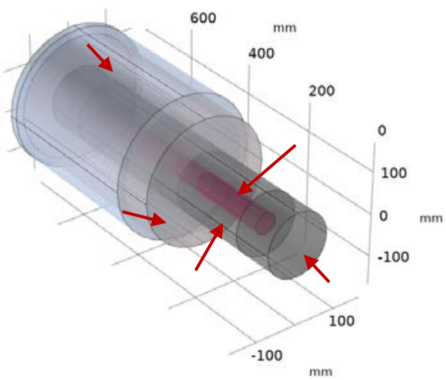
In 2023, the NWMO developed the scope of work and designed high-grade stainless-steel cells for the testing program. Ten (10) stainless-steel cells and ten (10) individual stainless-steel reservoir cells were manufactured as shown in Figure 4-15, and two reference waters (CR-10 and SR-290) were prepared in 2024. Figure 4-15 shows the test cell units with both bentonite and LHHPC specimens. The tests began in 2024, and will be examined at 1, 2.5, 5, 10 and 15 yearly intervals.

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

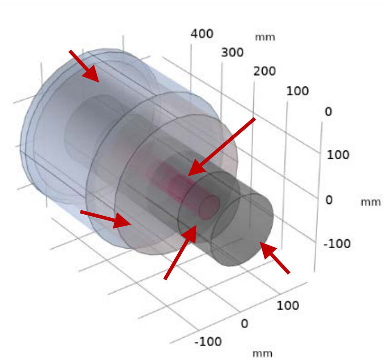
The NWMO has used fully coupled Thermo-Hydro-Mechanical (THM) CODE_BRIGHT models to study the unique NWMO placement concept since 2016. The THM numerical modelling of NWMO's placement room concept was focused on the evolution of the bentonite-based materials in the crystalline and sedimentary rock geospheres (i.e., CR-10 and SR-290). In 2024, the NWMO published a technical report (Malmberg et al., 2024; NWMO-TR-2023-05) on all of the numerical modelling work previously done by Clay Technology. This technical report details individual numerical modelling tasks that were conducted since 2016.

4.4.6 Thermo-Hydro-Mechanical Benchtop Experiments

In late 2018, the NWMO and its contractor (the National Research Council of Canada (NRC)) launched a work program to design and construct test cells to perform experiments examining the Thermal-Hydro-Mechanical (THM) response of bentonite buffer (HCB and GFM) for use as a component in the Engineered Barrier System of the multibarrier concept.

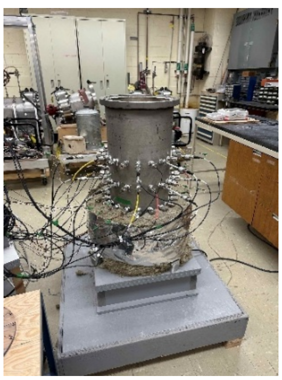


3D schematic of T apparatus

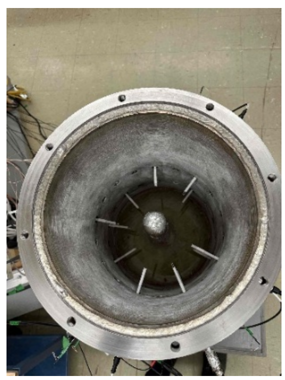


3D schematic of THM apparatus

Figure 4-16: Representative schematic of the T and THM test apparatuses



a. T test apparatus with two sensor zones



b. Heater and sensors installed

c. HCB and GFM placed

d. Final GFM layer placed

e. Final setup with insulation

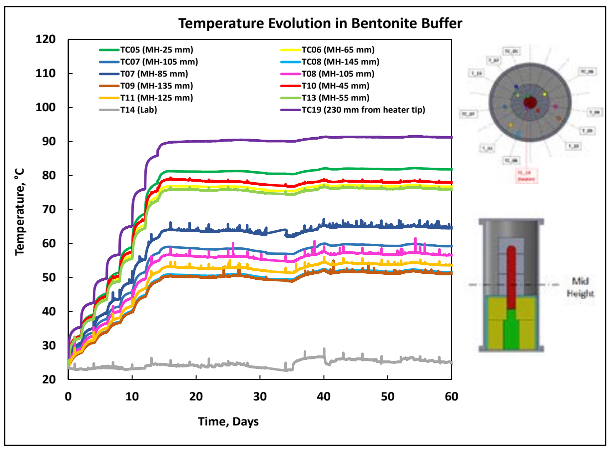
f. Data logging system

Figure 4-17: Installation of the T test

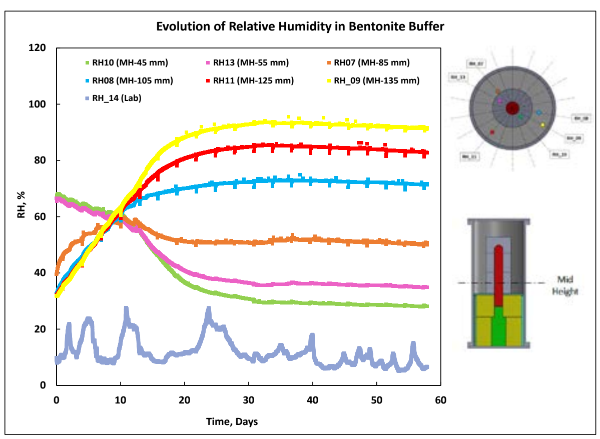
Two cylindrical experimental cells were manufactured; one to measure the THM response of the bentonite buffer when exposed to a temperature boundary condition (called T apparatus) and the other to measure the THM response when exposed to both temperature and hydraulic boundary conditions (called THM apparatus). Figure 4-16 shows a representative schematic of the T and THM apparatuses.

In 2022-2023, modification of the sensor layout and the heater design was completed, and sensors of moisture content and relative humidity were calibrated with different densities of HCB and GFM. A power meter and temperature controller were prepared for both tests. The NWMO undertook the T test at the NRC in December 2024. The T test apparatus was designed and manufactured to contain a heater along its length at its radial centre, surrounded by concentric layers of bentonite buffer. The heater maintains an interface temperature of 90ºC. A total of 32 sensors were installed in two zones (16 sensors in each zone as shown in Figure 4-17(a) to monitor temperature, moisture content and relative humidity in the bentonite buffer).

Figure 4-17 presents photos of the T test installation. In the T test, the moisture in the nearest bentonite is expected to be evaporated due to the high temperature induced by the heater, and the water vapour would then move to cooler zones of the buffer (i.e., GFM). As a result, the water content of the HCB is expected to decrease while that of the GFM will increase with time.



a. Evolution of temperature in the buffer



b. Evolution of relative humidity in the buffer

Figure 4-18: Evolution of temperature and relative humidity in the bentonite buffer

Figure 4-18 shows the evolution of temperature and relative humidity in the bentonite buffer after 60 days. The temperature was increased by 10°C every 48 hours until reaching the target temperature of 90°C. Figure 4-18(a) indicates a radial temperature gradient of 31°C across the bentonite buffer. Significant water vapour redistribution occurred across the buffer due to the thermal gradient as shown in Figure 4-18(b). The buffer system took about 32 days to reach the steady state of relative humidity.

The T test is ongoing with continuous monitoring until the end of 2025. The test results will provide useful information for advancing the design of the bentonite buffer seals and will be compared with numerical modelling.

5 GEOSCIENCE

5.1 GEOSPHERE PROPERTIES

5.1.1 Geological Setting and Structure

5.1.1.1 Mont Terri Seismic Imaging (SI-B) 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 CO_2.

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. Previous experience indicated that imaging structures at larger distance from the tunnel is significantly enhanced when wavefield acquisition in deep boreholes (several 10s of meters) is performed. Results of tomographic investigations of seismic anisotropy were published by Esefelder et al (2021).

In 2022, the next phase of the project (SI-B), Seismic Imaging of Structures Below the Mont Terri Tunnel and Rock Laboratory, to investigate the deeper structures below the tunnel (Figure 5-1). Previous seismic field tests have investigated relatively small source systems which are inappropriate for illuminating structures beyond ~100 m distance from the acquisition setup in claystone. It is the objective of this experiment to image geological structure down to the main thrust plane of the Mont Terri anticline at ~500 m – 1000 m depth below the tunnel. The wavefield will be recorded using receiver arrays in the safety gallery and additional borehole receiver arrays using available boreholes of ~80 m depth. During 2022, the installation of the receiver was completed, but the acquisition of the data (vibration at the shot points) was not completed due to personnel health considerations and postponed to 2023. Data set from this work were published in Wawerzinek et al 2022a and b and a journal paper was published (Wawerzinek et al 2022c).

In 2023, the majority of the experiment efforts were focused on modelling and logistics / planning for the mid-scale data acquisition task using mid-sized types of seismic sources (i.e., small vibro truck /mini-vib, accelerated weight-drop, explosives, magnetostrictive actuator source – four coupled single sources). Data acquisition using the mid-size sources (2023) and the associated data evaluation and interpretation (2023-2024) is preparation for the large-scale data acquisition task (primary experiment objective noted above) that will take place in 2024-2025.

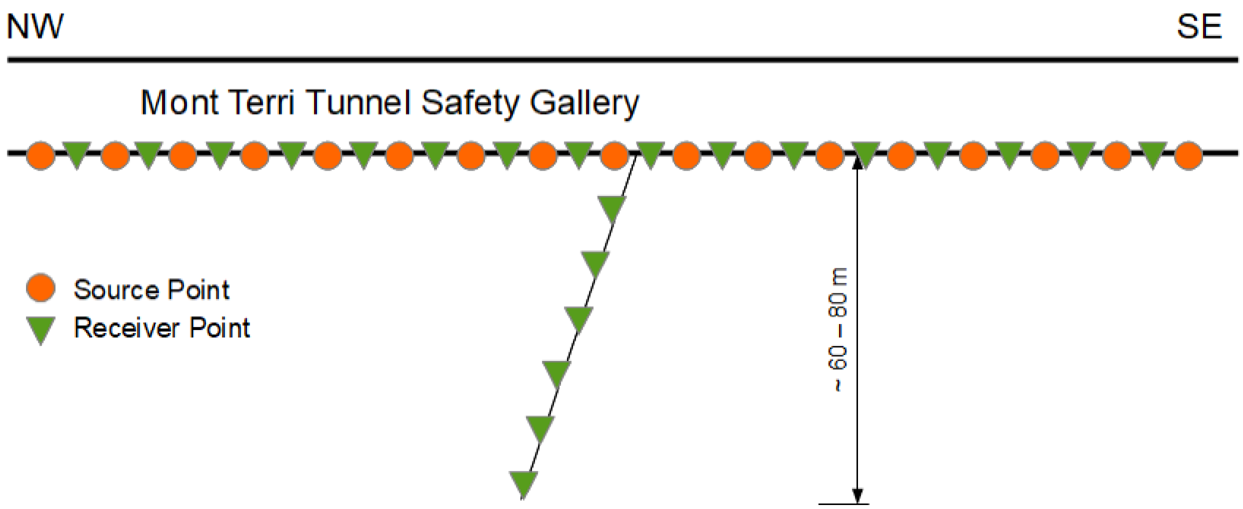


Figure 5-1: Conceptual Sketch of Seismic Acquisition Along the Safety Gallery in the Mont Terri Tunnel (cross-section, not to scale).

In 2024, in preparation of seismic investigations imaging the Mont Terri Anticline, the potential locations of profiles for the operation of a seismic vibro truck were identified. Seismic measurements were performed on the hills above the laboratory using a mid-size seismic vibrator truck. Geophones were placed along the two lines on the surface and along the Security Gallery in the rock lab, Figure 5-2.

Figure 5-2: GFZ Potsdam together with DMT performed a small seismic campaign on the roads on top of the rock laboratory.

Since the NWMO has selected a crystalline rock site for DGR, a decision has been made to discontinue our contribution in the seismic imaging (SI-C) experiment which is conducted on a sedimentary rock environment.

5.1.1.2 Metamorphic, Hydrothermal, and Diagenetic Alteration

5.1.1.2.1 Carbonate Paleogenesis

Based on the results of an ongoing regional study, conducted over the last decade exploring the origin of dolomite diagenesis in southern Ontario (Al Aasm et al 2021). The two deep boreholes drilled at SON/South Bruce for the DGR Project were sampled and the results were added to this study.

This study conducted a similar sampling program to the ones previously performed at the Bruce nuclear site and the OGSRL. Core samples were taken from the two deep boreholes at South Bruce and analyzed for petrographic, stable and Sr isotopes, fluid inclusion microthermometry and major, minor, trace and rare-earth elements (REE). The program further constrained the temperature of dolomite formation and fluid evolution within the Ordovician, Silurian and Devonian formations of southern Ontario.

The results were synthesized with the existing data to demonstrate that SON/South Bruce area can be reconciled within the regional model (Al-Aasm et al 2021, 2023) to provide useful insights into the nature of dolomitization, and the evolution of diagenetic pore fluids in this part of southern Ontario.

Key Areas of Study:

1. Continue to enhance knowledge of diagenetic fluid history by differentiating between basinal (regional) and hydrothermal (local) sources of diagenesis. Recent work suggest that the Silurian/Devonian systems have a separate and more recent fluid history. Further samples were needed to determine the number of fluid events and their relative timing.

2. Determination of Rare Earth Elements (REE) in both previously examined samples and new samples collected as part of this new work. REE’s were applied to distinguish between a meteoric, basinal and/or hydrothermal source fluid for the dolomitized carbonates and siliciclastics in South Bruce site.

3. Peer review of earlier fluid inclusion work undertaken at the South Bruce site by the British Geological Survey.

4. Results were in the form of a report to the NWMO with a paper(s) to be published.

During 2023 over 100 samples covering the entirety of the stratigraphy at South Bruce were taken from the two boreholes for study. These samples were analysed by the University of Windsor and results delivered in late 2024.

The results were synthesized with the existing data to demonstrate that South Bruce can be reconciled within the regional model to provide useful insights into the nature of dolomitization, and the evolution of diagenetic pore fluids in this part of southern Ontario. Since a crystalline rock site has been selected to host Canada’s DRG, this work will not continue.

5.1.1.2.2 Clumped Isotope Paleothermometer for Carbonates

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 (Δ_{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.

Key accomplishments over the project duration have included: 1) hiring of an experienced staff member to help lead the project, 2) the GSC instrumentation was optimized, 3) the required dolomite temperature calibration anchors were produced, 4) a data standardization scheme for dolomite was established, 5) the analysis of temperature calibration anchors to produce calcite-specific and dolomite-specific clumped-isotope geothermometers, 6) preparation of two manuscripts for publication in scientific journals, and 7) analysis of materials from the Bruce nuclear site was initiated. In 2023, the manuscript documenting the development of the "Franken-kiel" carbonate device, and the application of the first Δ47 temperature calibration for both calcite and dolomite with this instrument, was published (Fosu et al., 2023). In addition, the analyses were completed on core samples from the Bruce nuclear site, with the aim to contribute further to the understanding of fluid evolution in the Ordovician carbonates. A second manuscript, focused on the results of said analytical work, was initiated in 2023. In 2024, a draft of the manuscript was completed and has been revised after circulation with coauthors. The results corroborate the existence of a regional moderate heating event that affected both host rocks and associated secondary mineralization. The results were also presented at the International Clumped Isotope Workshop, through which constructive feedback was received. Submission of the manuscript to a journal is targeted for 2025.

Work in 2025 will focus on site-specific samples from the Revell Site (WLON-Ignace area), to assess if the calcite clumped isotope geothermometer can provide additional insights into the fluid evolutionary history.

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 on-going to continue the development of 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 2022, the database of hydraulic properties was expanded to include data on total dissolved solids concentrations, porosity, and tortuosity from sites across the Canadian Shield. A journal publication on these data, as well as their application in representative groundwater models for density-dependent flow was prepared.

In addition to expansion of the reference dataset of hydraulic properties for Canadian Shield settings, research was performed on developing methods for generation stochastic correlated random fields for both equivalent porous media rock mass and discrete fracture zones that are conditioned to known data. The stochastic generation of conditioned correlated random fields was also linked to methods for correlating variability in fracture zone properties, including fracture size, orientation, degree of openness, to the assigned transmissivities. Research in methods to enhance permeability at fracture intersections were investigated. Modelling approaches for computing marginal and normalized sensitivity coefficients were also investigated. These methods are planned to be applied to site-specific groundwater modelling for the Revell Site.

5.1.2.2 Hydraulic Properties of Sedimentary Rock

5.1.2.2.1 Anomalous Pressures − United States Geological Survey

Research by the United States Geological Service (USGS) continued to investigate the underpressures shales within the SON/South Bruce Site. This work program extension investigated: (1) a hypothetical rock-wellbore system that considered various hypothetical initial gas phase distributions and pressure profiles to study evolution of the system after the borehole was drilled and shut in. The area surrounding a single borehole was simulated over time scales representing measurement periods in the field. The results were used to examine how pressures measured in boreholes related to liquid pressures in the rock when a separate phase gas was present (2) the South Bruce site. Since the Cambrian is absent at the South Bruce site, the model it was run without it present. Simulations were performed representing multiphase flow and pressure evolution at: (1) the wellbore scale over time periods pertaining to the field measurement techniques, and (2) the site scale over geologic time periods. The results from these efforts were then be used to draw conclusions, which were disseminated to the scientific community via presentations and journal article (Plampin and Provost, 2022).

In 2023, the research was extended to consider whether the observed underpressures could be modelled in the case where the Cambrian sandstone, at the base of the Paleozoic strata, was not present. Since a crystalline rock site has been selected to host Canada’s DRG, this work will not continue.

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

In general, microbiological life in the subsurface is limited due to severe shortages of electron donors/acceptors and microbially degradable organic carbon sources. However, life is still possible in deep aquifer system or hydrocarbon reservoirs. While such features will not be in the immediate vicinity of the DGR, they will exist remotely and could impact the DGR. For example, if sulfate-reducing bacteria (SRB) are viable they can produce sulfide species which could migrate toward used fuel containers and cause 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 well justified and conservative in nature.

As part of NWMO's site characterization activities, samples of rock core, groundwater and porewater have been collected at various depths from NWMO boreholes in the WLON-Ignace and the SON-South Bruce area. Each sample is being analyzed using methods developed through applied research at multiple Canadian universities (Waterloo, Toronto and McMaster). Researchers from these institutions apply DNA, RNA, PLFA and NMR-based techniques to determine the type of organisms present, the activity of these organisms, and the potential for the organisms to grow in the rock or in groundwater. Analysis of these samples is ongoing but some initial results, initially published by Beaver et al. in 2021, have concluded that no microbiological life was detectable in the crystalline rock sampled from the Revell site down to 500 m depth. Currently, samples of core from approximately 500 – 750 m depth from a borehole in the South Bruce area are being processed along with water samples taken from a borehole in the Ignace area. Initial PLFA data suggests that SRB are not present in either case. Therefore, from current data the impact of microbes on the DGR is expected to be insignificant. However, more work in this area is required and is ongoing.

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 and 2022, 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 and 2023, the Canadian Shield component of the database was advanced (including thousands of data points). A journal article documenting observations on select geochemical parameters, arising from the compilation of the database, was published in 2024 (Boumaiza et al., 2024). The final database (containing data from various locations in the Canadian Shield) also was published to a data repository for scientific use (DOI:10.20383/103.01039).

Incorporating site-specific data from the Revell Site (WLON-Ignace area) into the developed Canadian Shield database, and a supporting report on process understanding, is a project that was initiated in 2024 at the University of Waterloo and will be completed in 2025.

5.1.3.3 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.

5.1.3.3.1 Porewater Extraction − Crystalline Rocks

A principal research activity has been developing a whole-core technique for extraction of porewaters from crystalline rocks using vacuum distillation. Vacuum distillation was established as a reliable method to extract porewater from low-permeability sedimentary rocks (Clark et al., 2013, Al et al., 2015) as an alternative to classical methods (e.g., centrifugation) that can be unsuccessful when attempted on rock samples of low water content.

The objectives of the crystalline research program were 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 results of this work have been documented in previous annual technical reports (NWMO, 2022; NWMO 2023a) and the method demonstrated as successful via repeated re-saturation and extraction experiments.

Given the success in developing a methodology to fully extract porewater from whole-core crystalline samples, the method was applied in 2022-2023 to extract porewater from archived cores collected from the Revell Site (WLON and Ignace area). A technical report, documenting the method development work and the benchmarking, and the testing on cores from the Revell Site, was submitted to NWMO for review in December 2023 and was published early in 2024 (Najem et al., 2024; NWMO-TR-2024-04). Following the publication in 2024, work was then initiated that aims to demonstrate the crystalline rock extraction method using preserved cores from the most recently drilled boreholes (IG_BH05-IG_BH06) from the Revell Site (WLON-Ignace area), which can be compared to data collected for site characterization purposes using the out-diffusion and isotope diffusive exchange techniques. This work will be completed in 2025, with the intent to demonstrate method applicability for low water content (<1% by volume) crystalline rock samples. A technical document will be compiled in 2025, as an addendum to NWMO-TR-2024-04, for this final method demonstration exercise. The method has potential applicability in future detailed site characterization activities given the site selection decision.

5.1.3.3.2 Porewater Extraction − Sedimentary Rocks

Work at the University of Ottawa has focused on the extraction of porewater from rock cores into cellulosic papers for analysis of the porewater composition. Known as the Paper-Absorption, or PA method, it has been under development for several years.

Recent work (2021-2024) focused on a) testing the PA method using samples of the shale facies of the Opalinus Clay from a collaborative experiment at the Mont Terri underground laboratory in Switzerland (as part of the PC-D Experiment), and b) further refining understanding of adsorption of higher-valence cations on the cellulose. The data from the Opalinus Clay demonstrate excellent correspondence with the best available cation and anion data reported in the literature (Wersin et al. 2022). The PA method was used as a part of porewater characterization activities at the South Bruce Site (2022-2023), along with already-established methods for the sedimentary units such as vacuum-distillation extraction and aqueous leaching.

The method is unique in that it specifically provides information on the mobile porewater, rather than a combination of mobile and bound water. The PA method was presented at the June 2024 NEA Workshop on Porewater Chemistry of Clayrocks in Repository Environments and a NEA Technical Report summarizing the workshop presentations, discussions and poster contents will be released by the NEA in 2025 (titled: *Proceedings of the Workshop on Porewater Chemistry of Clayrocks in Repository Environments*).

5.1.3.4 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 clays and other minerals. There is potential for modification of original porewater H- and O-isotope compositions from exchange between porewater and structural H and O in clay minerals, and H- and O-isotope fractionation between mobile and bound water, depending on the method of porewater analysis.

Research at Western University has been summarized in previous annual technical reports (NWMO 2022, NWMO 2023a) focuses on the H- and O-isotope compositions of clay minerals in Ordovician shales from the Bruce Nuclear Power Generating Station (Bruce nuclear site) to try to understand the impact of these processes. Data collected to-date from this work has suggested that isotopic exchange with clay mineral structural H can modify porewater H-isotope compositions in low water-content shales.

In 2024, the following tasks were advanced, or completed, as summarized below and in Longstaffe et al. (2024):

1. Complementary to the earlier (2023) eight-week experiments, incubation of twenty (20)- and forty-six (46) week O- and H-isotope exchange experiments between Bruce Site <2μm size-fractions and freshwater at 90°, 120°C and 150°C was completed in 2024 and isotopic analysis of these samples undertaken. Parallel 8-week experiments were also completed but in this case using the NWMO synthetic brine composition (Yang and Kennell-Morrison, 2021) rather than freshwater. Interpretation of these data is in progress. The results broadly confirm *not only* significant H-isotope exchange *but also* O-isotope exchange between clay minerals and fresh or saline porewater at these temperatures. The longer-duration experiments test the rate of this isotopic exchange and the brine experiments test the effects of high Na^+, Ca^{2+} and Cl^- concentrations on clay mineral-water isotopic exchange.

2. The coupled Thermogravimetric Analyzer-Cavity Ringdown Spectrometer (TGA-CRDS) instrument under development is intended for measuring changes in mobile porewater isotopic composition due to fractionation between clay-bound water and mobile porewater. In 2024, (i) the instrument met QA/QC specifications for measurement of mass change (TGA) and $\delta^{18}O$, $\delta^{2}H$ and water content for both liquid water and water vapour (CRDS); (ii) quantitative transfer of water from sample (TGA) to detector (CRDS) was achieved using a capillary transfer line and dry nitrogen as carrier gas, (iii) a method was developed to introduce calibration standards into the TGA, and (iv) satisfactory accuracy and precision for $\delta^{18}O$ (better than ±0.3‰) and

δ^2H (better than ±2‰) was achieved on the VSMOW-SLAP scale for freshwater standards analyzed by TGA-CRDS.

The research on clay-bound waters was presented at the June 2024 NEA Workshop on Porewater Chemistry of Clayrocks in Repository Environments and a NEA Technical Report summarizing the workshop presentations, discussions and poster contents will be released by the NEA in 2025 (titled: *Proceedings of the Workshop on Porewater Chemistry of Clayrocks in Repository Environments*). The clay-bound waters research and supporting technical documents will be completed in 2025.

5.1.3.5 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 hydrogen-1 reservoirs in the rock, to quantify diffusion coefficients for H_2O as well as to image the degree of heterogeneity of the hydrogen-1 distribution in the samples.

The final NEA CLAYWAT Project report was formally submitted to the NEA for publication in 2023 and in the final stages of NEA review for publication by year-end 2024. The NEA CLAYWAT Project has officially closed with submission of the final report to the NEA. The report is to be published by the NEA in 2025.

5.1.3.6 Porewater Gases - Mont Terri PC-D Experiment

The NWMO has led the Porewater Gas Characterization Methods (Non-inert and Noble Gases): Field and Laboratory Methods Comparison (PC-D) Experiment at the Mont Terri URL since 2019. The objectives of the experiment are to: 1) compare results obtained for noble gas concentrations and isotopes using methods currently employed by nuclear waste management organizations (via established analytical laboratories) – with the aim to assess the comparability of results using different laboratory extraction procedures on 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 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. In addition, the PC-D Experiment provided an opportunity for application of the PA porewater extraction and characterization method (see Section 5.1.3.3.2).

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 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). Over the course of 2022, the laboratory analytics began, and several analyses (short-term) were completed.

Long-term analyses were completed by two of the participating laboratories in 2023, and the third laboratory completed analyses by year-end 2024 (on samples that were preserved in stainless-steel canisters for ~1.5-2 years longer than the other participating laboratories). Reporting was initiated on the methods, analytics and non-inert gas results in 2024. The final data compilation and overall findings of the study will be summarized in a Mont Terri Technical Report in 2025, bringing the PC-D Experiment to a close. In 2024, the PC-D Experiment results were presented at the Annual Mont Terri Technical Meeting in St. Ursanne, Switzerland (May), and at the 9th Clay Barriers Conference in Hannover, Germany (November).

5.1.3.7 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 2024, work as a part of GD was focused on the following projects: 1) assessment of trace elements in porewaters, and 2) nitrogen-system dynamics in clay media (phase 2).

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 fracture permeability of Lac du Bonnet (from western flank of the Canadian Shield) under different stress conditions.

5.1.4.1.1 Permeability Characteristics of the Lac du Bonnet Granite

Steady state permeability experiments were conducted to study permeability of synthetically fractured specimens (fractures nearly parallel to the core axis) under confining stresses during loading and unloading. Fracture permeability was estimated using laboratory data. Moreover, geometric features of the fracture surface were characterized using advanced scanning technology. Fracture scan data was used in COMSOLTM Multiphysics for numerical estimation of fracture aperture change with stress as well as estimation of permeability. The project was completed in 2023, and a journal article was published in 2024 (Huo et al, 2024).

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 recent work has focused on optimizing measurement parameters for tracer experiments. The instrument has been modified 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. Both the X-ray absorption and fluorescence approaches have been successfully developed to monitor iodide and cesium diffusion in Queenston Formation shale and the data demonstrate that beam hardening effects are virtually eliminated.

Work in 2024 focused on pursuing the X-ray fluorescence technique, which has the unique potential for monitoring simultaneous diffusion and reaction processes (e.g., I^- and Cs^+). To date, among the X-ray measurement techniques developed, the fluorescence spectroscopy is proving to be the most sensitive. This sensitivity is necessary when applied to low porosity samples such as crystalline rock (e.g., granite).

During the Spring and Summer of 2024, method-development experiments measuring I^- diffusion on samples with less than 1% porosity were successful. In the Fall of 2024, the system was modified and tuned to allow measurement of porosity profiles along the diffusion path in low-porosity samples by X-ray absorption spectroscopy. If successful, this will improve on the ability to measure spatial variations in porosity, reactivity and D_e compared to the previous approach which assumed a homogeneous porosity. This will allow assessment of reaction and transport properties in key regions with heterogeneous diffusion and mineral characteristics, such as altered fracture-matrix interfacial zones. In early 2025, X-ray spectrometric measurements will begin on Revell (WLON-Ignace) and South Bruce cores collected during the site selection program for APM.

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 active HTO, Cl^- and I^-), one borehole targets the central part of the main fault zone, and the second one targets 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 expected; and iii) to investigate if enhanced anisotropic permeabilities with respect to undisturbed shale zone are present. In 2023, two boreholes were drilled. The filter unit, pack systems and the circulation system were installed. The diffusion interval was saturated with the artificial porewater. In 2024, a tracer cocktail was injected, and the diffusion experiment will last for 3 years. The circulation fluid was sampled regularly to monitor the tracer concentrations.

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 has lasted for 4 years. An international joint CI/CI-D modelling team has been modelling the alteration due to cement-clay interaction and the tracer transport across such interfaces with different reactive transport codes including MIN3P-THCm (e.g., Su et al. 2022; Prasianakis et al. 2022). The overcoring of three boreholes including the one containing the radionuclide circulation experiment was completed in 2023. The overcores were segmented and processed to obtain profile information across claystone/concrete interfaces, and within concrete body and surrounding Opalinus Clay. Over 250 samples were prepared for aqueous extracts (mainly for ^{36}Cl and ^{3}H measurements) and water-content measurements. In addition, overcored samples from the CI-D experiment included the OPC / OPA interface characterized as a part of the CI Experiment. The interface samples collected in 2023 were analysed with support from the CI Experiment in 2024 to assess: 1) mineralogical alteration and the extent of alteration zones, and 2) the evolution of porosity. Chloride concentrations in aqueous extracts of solid samples from overcoring and chemical composition of the circulation fluid will be documented in a Nagra technical note in 2025. Reactive transport modelling will be performed to interpretate the overcore data.

5.1.4.3 Sorption

Sorption is a mechanism for retarding sub-surface radionuclide transport from a DGR to the environment. The NWMO has developed a sorption distribution coefficient (K_d) database for elements of importance to the safety assessment of a DGR for highly saline conditions in Canadian sedimentary rocks (Vilks and Yang 2018).

Researchers at McMaster University continue to systematically study sorption properties of Se, Tc, U and Eu on limestone, shale, illite and bentonite (MX-80) in Na-Ca-Cl solutions (ionic strength 0.1 M to 6.0 M) including a reference porewater SR-270-PW brine solution (Na-Ca-Cl type with an ionic strength 6 M), as well as on granite and bentonite in Ca-Na-Cl solutions (ionic strength 0.05 M to 1.0 M) including a reference groundwater CR-10 (Ca-Na-Cl type with ionic strength 0.24 M), under reducing conditions for Se, Tc and Eu (Walker et al. 2022; Racette et al. 2023; Nagasaki 2024a; Nagasaki et al. 2024a, 2024b), and under both oxidizing and reducing conditions for U (Zheng et al. 2024a, 2024b). The effects of ionic strength and pH (4-10) on the sorption of Se(-II), Tc(IV), Eu(III), U(VI) and U(IV) on shale, illite, limestone, bentonite and granite have been investigated (Walker et al. 2022; Yang et al. 2022; Racette et al. 2023; Nagasaki et al. 2024a, 2024b; Zheng et al. 2024a, 2024b, Nagasaki 2024a, 2022). The two-site protolysis nonelectrostatic surface complexation and cation exchange sorption (2SPNE SC/CE) model successfully predicted the sorption of Eu(III), Se(-II), Tc(IV), U(VI) and U(IV) on MX-80, illite and granite, and the optimized values of surface complexation reaction constants were estimated (Yang et al. 2022; Racette et al. 2023; Zheng et al. 2024a, 2024b; Nagasaki et al. 2024a, 2024b; Nagasaki 2024a). The sorption study of Eu and tetravalent U(IV) on granite and bentonite in Ca-Na-Cl solutions and on limestone, shale, illite and bentonite (MX-80) in Na-Ca-Cl solutions will be published in three journal papers in 2025. The sorption mechanism of Se(-II) on biotite under reducing conditions was studied by density functional theory (DFT) simulation and will be published in a journal in 2025.

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 and using preserved crystalline cores from IG_BH01 from the Revell Site (WLON-Ignace area). Samples from the Queenston, Georgian Bay, Blue Mountain and Collingwood Member formations were evaluated (rock types included claystone, marl and limestone), as well as the granodiorite-tonalite from IG_BH01 at depths between 310 and 840 m depth along borehole. 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?), and the applicability of different exchange mechanisms to successfully measure CEC in such rock types. The main findings of this work were compiled into a Technical Report for the NWMO in 2019. The final technical report will be published by the NWMO in 2025.

5.1.5 Geomechanical Properties

5.1.5.1 In-Situ Stress

The StressBay project on quantification of *in situ* stress commenced in 2020. The main research focus during the first half of 2024 was applying Bayesian segmented linear regression and other advanced statistical techniques to the analysis of *in situ* stress. In parallel, a new methodology was developed for generating informative priors. This is a significant development, as it allows formal incorporation of knowledge relating to *in situ* stress at a project site into priors for subsequent Bayesian linear regression analysis. As a result, reliable estimates of a design stress state can now be produced using fewer *in situ* stress measurements than previous techniques required. This research was summarized and presented in a poster at the annual NWMO Geoscience seminar 2024 (Javaid and Harrison, 2024) and two conference papers (Javaid et al, 2024a and b).

Phase I of this research project (StressBay I) was concluded in May 2024, with Phase II (StressBay II) commencing immediately thereafter. This phase will focus on developing protocols for *in situ* stress characterization as a critical design parameter for nuclear waste repositories. During the second half of 2024 the protocol framework has been systematically developed, including defining key features and disassembling *in situ* stress characterization analyses into detailed components within the protocol mapping and operational procedures.

The following two conference papers and one poster were published and presented in 2024: Javaid et al.,2024a and b; Javaid and Harrison, 2024.

5.1.5.2 Rock Properties from Laboratory Experiments

The Queen's Geomechanics and Geohazards Group, QGGG, has continued experimental rock mechanics research studies. An overview of this work is provided in Section 5.2.4.1 Excavation Damaged Zone.

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

5.1.5.3.1 POST Project

The planned test program was completed last year and the work this year was focussed on analyzing the results and preparing a series of laboratory reports which describes the material, procedures and results. Work with a summary report which gives the overall picture of the background, scope and results was also conducted.

The analysis of the results mainly concerned extracting standard parameters from the normal loading and direct shear tests, but also an analysis of the effect of fracture scale using the results from the three tested fracture sizes (35 × 60 mm, 70 × 100 mm and 300 × 500 mm), and two fracture types (natural versus tensile induced). Some evaluations were made on the results from the contact pressure distribution measurements and fracture geometries as a mean to interpret the mechanical test results. The main part of the analysis work was made within the associated PhD-project funded by the Rock Engineering Research Foundation in Sweden (BeFo) and with collaboration of a guest researcher from the University of Vigo in Spain hosted by the Royal Institute of Technology (KTH) in Stockholm.

Results from the normal loading and direct shear tests of the largest fracture size (300 × 500 mm) were presented at the national rock mechanics and rock engineering conference Bergdagarna in Stockholm in March 2024 (Jacobsson et al 2024).

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.

Between March 2023 and March 2024, a planned increased power step was completed. Field data acquisition and interpretation as well as numerical modeling are ongoing.

The NWMO will decide in 2025 in which experiments to remain as an active partner at the Mont Terri URL, given the site selection decision.

5.1.5.3.3 Shear Induced Pore Pressure Around Underground Excavations

Argillaceous (clay-rich) formations represent the most common sediments on the surface of the earth, and countries with argillaceous formations such as Canada, France, Belgium, Japan, Switzerland and the United States have been investigating low-porosity, low permeability argillaceous rocks to assess their potential as caprock or host rock for CO_2 storage and nuclear waste disposal. One of the prominent argillaceous rocks that is being considered for nuclear waste disposal is “shale”. In soil and weak rock like shale where the connected porosity is greater than 20%, hydro-mechanical coupling occurs. In shales, geomechanical processes are a function of these complex rate and coupled phenomena and are still misunderstood from a design perspective. To validate our understanding of these processes and to overcome existing knowledge gaps, in-situ field measurements supported with extensive laboratory tests are needed.

In order to achieve this longer-term objective of validation of our understanding, the following shorter term objectives of this research project have been completed: (1) development of a method to measure pore pressure (u) locally on a shear zone during a triaxial test to evaluate the limitations of these measurements in shales; (2) analysis of measured u from a mine-by experiment at the Mont Terri Laboratory; (3) numerical modelling of the mine-by experiment to determine the change in total stresses during tunnelling; (4) evaluate the measured u, and changes in total stress to determine effective stress paths, and pore pressure parameters; and compare these to the strength and yield surfaces identified by others.

The development of a method to measure pore pressure locally on a shear zone, objective (1) was completed using fibre optic sensors and a draft journal paper has been prepared. The technical aspects of Objectives (2), (3) and (4) have been completed. These results are currently being assembled into a journal paper.

5.1.5.3.4 Rock Mass Effective Properties

This study aims to quantify the effective mechanical properties of rock masses from a DFN approach. The current phase of the project started in the last quarter of 2023 and will continue until the end of 2026.

During 2024, further simulations and analyses were first carried out to investigate the role of the fracture mechanical properties on the effective strength of the rock mass under uniaxial or unconfined conditions. The selected parameter was the fracture shear stiffness (k_s). A numerical sensitivity study was started with k_s in the range [0, 2, 5, 10, 20, 50] GPa/m and numerical simulations were performed for several of the DFN models and realizations selected from the previous steps of the project. The evolution of peak rock mass stress and peak strain as a function of the fracture shear stiffness was analyzed. In addition, several exploratory analyses were performed to track and understand the evolution of the micro damage in the rock mass during the UCS test. The first metric tracks the spatial location of the damage (micro cracks) during the UCS test, particularly in relation to the vicinity of the DFN present in the rock sample at the start of the test. The second metric reflects the increasing contribution of the initial DFN to the rock mass strain, measured for each fracture individually. The evolution is interpreted using the so-called Lyapunov model which is often used in studies of dynamic systems that are highly sensitive to initial conditions. The third line of investigation focuses on the entire spatial pattern (initial DFN and new damage) of the failure path that develops during the UCS test and up to the peak stress. During the numerical simulation, each new crack in the rock mass is added as a micro fracture to the initial DFN. At each step during the loading this

DFN is analyzed to characterize the development of a failure path and the presence of rock bridges.

In parallel, a poster was presented at the NWMO Geoscience Seminar in June 2024, and a journal paper is in preparation. The focus of the poster and paper is on the fundamental understanding of the effect of DFN geometric structure on rock mass strength, in UCS and tensile conditions. In addition a conference paper (Lavoine et al. 2024) and an oral presentation were prepared for the Eurock conference in Alicante in July 2024. The latter focused more on the technical and numerical aspects of the project.

5.1.5.3.5 Permeability

The aim of the project is to improve the fundamental understanding of the role of stress in the variation of bulk permeability in fractured rock masses - intensity, anisotropy and scale aspects - and to develop a quantitative and DFN-based relationship to factor the permeability/stress dependence in hydrogeological scenarios for post-closure safety assessment. The current phase of the project started in the first quarter of 2024 and will continue until the end of 2025. In 2024, two tasks have been addressed.

During the first half of the year, we investigated how the interpretation of in-situ flow logs contributes to constrain the fracture transmissivity/stress law and the bulk permeability (Task 2 of the current phase). To this end, numerical simulations were performed and compared under spherical (and cubic) permeameter (Darcel et al., 2024) and Posiva flow log-like conditions. A range of DFN models were tested, from simplistic to more realistic. Analyses showed firstly that flow log interpretations, taken as the sum of individual inflows along a borehole section, can be related to the average hydraulic conductivity that is predicted by numerical upscaling and spherical permeameter based tests. A second set of analyses demonstrated how and up to which extent in-situ flow logging data could be used to calibrate DFN fracture transmissivity models.

During the second and third quarters, Task 3.1 was completed. It is about the effect of stress redistribution around a tunnel at depth, on both fracture transmissivity and bulk permeability. Analytical predictions and numerical simulations were combined. The numerical model was developed based on a coupling between DFN.lab and 3DEC. DFN generation, connectivity analyses and flow simulations are performed in DFN.lab and mechanical stresses are performed in 3DEC. The results of the Task are summarized in a proceedings paper that has been submitted and accepted (early February 2025) for a presentation at the Eurock 2025 conference planned in July in Trondheim.

In parallel, we submitted the journal article from Phase II of the project in March 2024. The paper (Darcel et al., 2024) was accepted for publication in Engineering Geology in August 2024.

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 2022, the incorporation of the latest PISM (Winkelmann 2011) based ice-dynamical core with coupled proglacial lakes, as well as approaches for representing surface drainage was refined, with a focus upon deglaciation and meltwater outflow in the St. Lawrence River area. The two main advances in the development of GSM were:

1. Incorporation of latest PISM-based ice dynamical core, with fully coupled proglacial lakes.

2. Development of graphical and postprocessing scripts for representing surface drainage results.

To support NWMO investigations into the impacts of glaciation on the geosphere, a glacial boundary condition interim dataset was provided, and includes timeseries data for icesheet thickness, depth of permafrost, and basal temperatures. Details of the interim data delivery are documented in Stuhne and Peltier (2023). In 2024 model development work continued to incorporate these development changes and a technical report is expected in 2025.

5.2.1.2 Crustal Rebound Stresses

This project was initiated in 2022 with the Swedish Land Survey (Lantmäteriet) and was completed in late 2023. The objective of this work program was to estimate the maximum glacially induced transient horizontal and vertical stresses for a range of depths at discrete intervals from the surface to below the deep geologic repository (DGR) horizon (down to several kilometers) around both the Revell and South Bruce sites. The depths examined for a deep geological repository at the Revell site were 500 m, 650 m, or 800 m. In South Bruce, the host rock formation (Cobourg limestone) occurs at a depth of approximately 650 m. Stresses were calculated with models that describe glacially induced lithospheric flexure and relaxation of the mantle over a time scale representing at least one full glacial cycle based on a new ice model for North America. The knowledge acquired through this work program was used as input to long-term geomechanical stability analyses for both sites and will support safety assessments conducted by the NWMO. The calculated rebound stress components, when superimposed on the more contemporary lithostatic and tectonic stresses, form the “total stress” of the in-situ stress regime.

The study makes use of updated boundary condition datasets from the ICE-7G models from the University of Toronto Glacial Systems Model (GSM) to calculate the maximum horizontal and vertical glacially induced stresses for a glacial cycle (using the timesteps from ICE-7G) in the areas of the two sites considered in the site selection process.

Elements of the work plan included:

1. Test of model resolution for most accurate stress determination and simultaneously efficient use of computation time.

2. A brief review of the current knowledge of the subsurface structure in continental Canada and the regions surrounding the sites of interest.

3. Construction of stratified and three-dimensional complex GIA models.

4. Computation of the spatial and temporal evolution of the total glacially induced stress field which is a summation of the contributions from the evolving weight of the glacier ice, the melted ice water, and the oceans. The stress field also included bending/fiber stresses and the migration of stress from the mantle to the lithosphere due to the loading. The faults before the onset of glaciation are assumed to be near equilibrium.

5. Investigation of sensitivity effects due to mantle viscosity, surface and mid-crustal weaknesses, and lateral heterogeneity in crust, lithosphere, and mantle.

6. Identification of areas for future research related to the understanding of faulting induced by glacial loading and unloading.

This project was completed in late 2023 with the deliverable of isostatic stress calculations for both sites. The work, and the associated outputs are documented in a journal article, which was published to JGR Tectonics (Steffen and Steffen, 2024).

5.2.1.3 Glacial Erosion – Dalhousie University

The previous scope of work included two objectives. A state-of-the-science review of published information relating to glacial erosion in crystalline bedrock settings. A paper was submitted to Nature Geoscience and a revised version is expected to be accepted in 2025. A second, more comprehensive manuscript for submission to *Earth Science Reviews* will be completed in early 2025.

Starting in 2022 research focussed on four separate methodologies that will help the NWMO assess rates of erosion at the proposed sites. These are:

1. Testing of the muogenic nuclide paleotopometry method.

2. Testing of the muogenic nuclide paleotopometry method on the Canadian shield.

3. Relative erosion efficacy under different ice sheet velocities.

4. Stratigraphic chronology required to determine why some regions escape ice sheet erosion.

This work will be published in a series of papers:

1. Muon Paleotopometry – Horizontal Method.
2. Muon Paleotopometry – Vertical Method.
3. Collection of underground samples to test muon flux methodology.
4. GIS, sampling, and mapping of Newfoundland Ice Sheet (NIS) ice dynamics.
5. Newfoundland sub-glacial erosion.
6. Saprolite/regolith and pre-Quaternary tills from the St. James Lowlands.
7. Subsampling of selected pre-Wisconsinan tills in Alberta.

These tasks will be completed and papers detailing methodologies and results will be submitted by the end of 2025.

5.2.1.4 Glacial and Proglacial Environment – Numerical Modelling

5.2.1.4.1 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. 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.

With BGE and BMWK joining the CatchNet program in 2022, CatchNet has four full members (SKB, NWMO, RWM and BGE) and two supporting members (COVRA and BMWK). Each full member funds a PhD student or postdoctoral fellow to work on a research topic related to cold-climate conditions.

In 2024, with additional financial support from NSERC, CatchNet funded a two-year postdoc position to be based at Dalhousie University. This postdoc program will start in 2025 with the focus on permafrost modelling in a fractured rock setting.

As a full member of CatchNet, 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.

In 2022, a working FEFLOW groundwater flow model was developed for Wolf Creek Research Basin (~ 195 km^2) in the southern mountainous headwaters of the Yukon River Basin in the subarctic region of northwestern Canada, Yukon. This model is used to investigate the effect of permafrost distribution on groundwater travel. Results of this study (Petersen et al. 2024) demonstrate the complexity of groundwater – surface water interactions in permafrost environments, including the importance of three-dimensional analysis in understanding cryohydrogeology and how permafrost distribution greatly affects fluxes and associated groundwater residence times.

In 2022, NWMO supported another PhD program based at the University of Laval with the focus on numerical modelling of permafrost-impacted groundwater flow systems. In 2023, a 2D modelling of hypothetical geosphere setting in the Canadian Shield was initiated to assess the impact of permafrost growth and decay cycles on groundwater flow and thermal conditions relevant to the near and far-field environment of a DGR. The goal of this study is to examine how transient events linked to long-term climate change and glacial cycles may affect the evolution of a deep groundwater flow system. Simplified conceptual models on relevant spatial and time scales are developed in part from field data and insights gained from a northern research site located near Umiujaq, in Nunavik, Quebec, Canada. Future climate transitions are based on the past one million years of air temperature data, which are considered an analogue for future changes. Simulated processes include coupled groundwater flow, heat and mass (brine) transport, with freeze/thaw, latent heat and ice-fraction dependent relative permeability. Results of this study (Malmir et al. 2024) reveal how permafrost cycles can affect deep groundwater pathways, leading to the formation of a transient barrier that restricts groundwater flow and brine transport between the geosphere and biosphere, potentially leading to longer flow and transport pathways and increased groundwater residence times.

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.

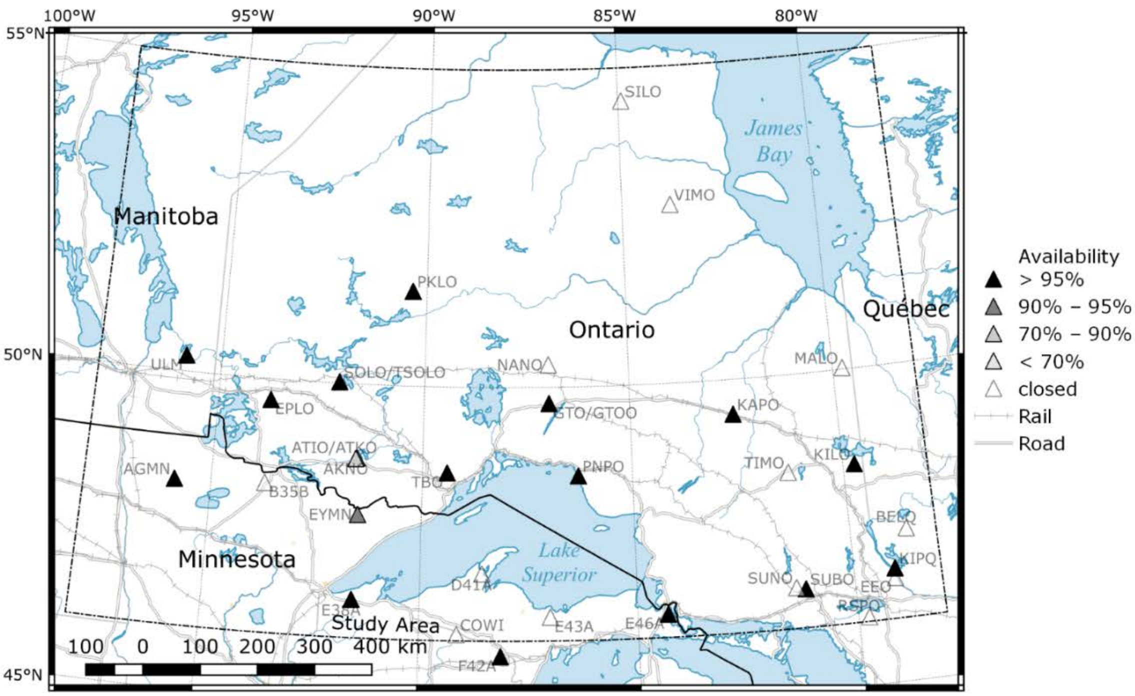
Unstructured grid capabilities were recently implemented into the multi-component reactive transport code MIN3P-THCm for 3-dimensional (3D) systems, including the parallelization of the unstructured grid functions (Su et al. 2022; Su et al. 2021; Su et al. 2020).

In 2024, researchers at the University of British Columbia and the University of New Brunswick performed: (1) reactive transport modelling of noble gas ingrowth, transport, and attenuation in sedimentary rocks; (2) development of reactive transport modelling methods for sparsely fractured granitic rocks; and (3) initiated grid design for stylistic reactive transport simulations of oxygen ingress and attenuation in fractured rock for conditions at the Revell site. Specifically, progress has been made by further developing a general formulation for the ingrowth of noble gas isotopes (He, Ne, Ar, Kr and Xe) and refining its implementation in MIN3P-THCm. The new extension was applied to simulate noble gas ingrowth in the Michigan Basin, demonstrating its suitability to investigate natural ingrowth of ^{4}He and ^{40}Ar in sedimentary rocks. The influx of noble gases from the Precambian basement rocks was included. The formulation for partitioning of entrapped gases between the aqueous and gas phases was further tested and refined to investigate the partitioning behavior of noble gases in the presence of a gas phase consisting predominantly of CH_4. The sorption of noble gases onto organic materials present in sedimentary formations was also included and evaluated. In addition, refined reactive transport modelling capabilities for fractured media have been implemented in MIN3P-THCm. The utility of a quadrilateral mesh discretization has been demonstrated for investigating O_2 ingress in large-scale fractured rock simulations. Results indicate a substantial improvement in efficiency for reactive transport modelling in porous media with fracture networks. A paper is currently in preparation for submission to an international peer-reviewed journal. In addition, grid design that will support stylistic simulations of oxygen ingress and attenuation for conditions representative of the Revell Site has been initiated, using the newly developed discretization method.

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 (Figure 5-3).



Notes: The study area is outlined with a dash-dotted line. Historical and currently active stations are shown as triangles, with the triangle filled according to data availability for 2022–2023. Most of the stations shown as “unavailable” are former FedNor stations which were mainly active 2006–2009; exceptions are EEO and SUNO, which were replaced by KIPQ and SUBO, respectively, in 2018. Historical analog stations are not shown.

Figure 5-3: Seismograph Stations in Northern Ontario, 2019–2023.

This program has been ongoing since 1982 and is currently supported by a number of organizations, including the NWMO. CHIS now provide monitoring of both northern Ontario and southern Ontario. 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 these regions.

During 2022–2023, 230 earthquakes were located in the northern Ontario study area, ranging in magnitude from 0.8 to 3.4 m_N. The pattern of seismicity generally conformed to that of previous years, except for two new clusters of low-level seismicity near Cat Lake, at the northern edge of the Severn Highlands seismic zone, and south of the Woodland Caribou Provincial Park, just east of the Ontario-Manitoba border. The largest earthquake was an event at 14 km depth, 58 km west of Chisasibi, QC, on the eastern coast of James Bay. Only one earthquake in the study area was felt, a small magnitude 1.8 m_N earthquake in Alban, ON fixed at a depth of 2 km.

With the NWMO selecting WLON-Ignace area as its site for a DGR, regional seismic monitoring in the SON-South Bruce area will be discontinued. It is likely that the NWMO will move the new microseismic monitoring network stations from the SON-South Bruce area to the WLON-Ignace area in 2025 to enhance microseismic detection capabilities.

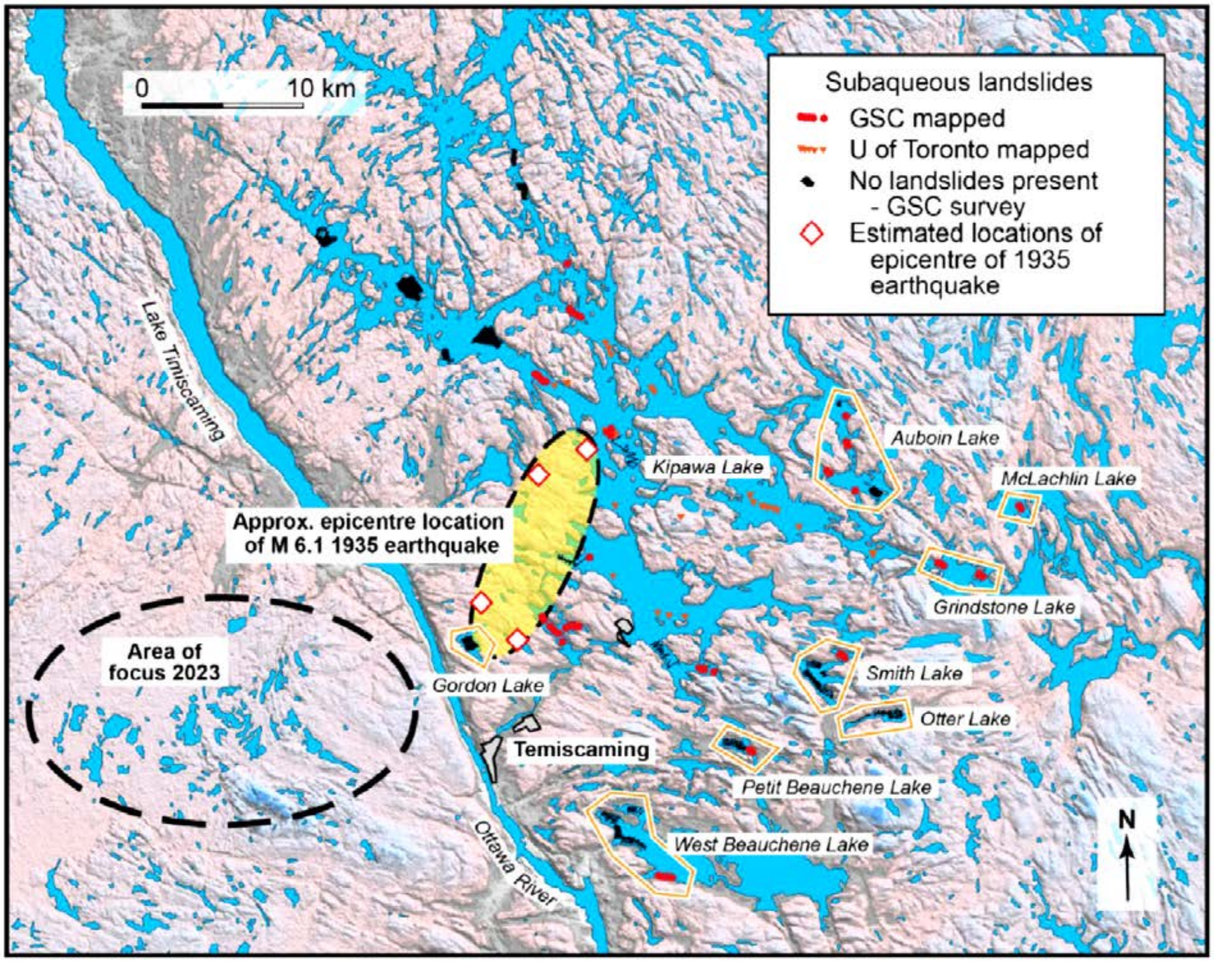
5.2.3.2 Mont Terri Nanoseismic Monitoring (SM-C) Experiment

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. During 2023, upgrades were finished and all tiltmeters digitized. The tiltmeters are used in several experiments for long-term and short-termed events such as CO_2 injection tests that commenced in November 2022 and continued through 2023. The results of previous injection experiments are published in Guglielmi et al. 2021 and Zappone et al. 2020. Over the course of 2024, the experiment involved ongoing maintenance and data collection / monitoring.

5.2.3.3 Paleoseismicity

Due to the long-life cycle of a repository, potential perturbations from ground motions associated with rare strong earthquakes require 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 2023, a continuing 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. A summary of the work conducted over the last decade was published in the Past Global Changes magazine (PAGES), Brooks, 2024. An open file report concerning the 1935 Temiskaming earthquake will be published (Brooks et al., 2024) (Figure 5-4).



Notes: Young subaqueous landslides identified in sub-bottom acoustic surveys (red circles – GSC unpublished data; orange triangles – after Doughty et al., 2010). The locations surveyed in August 2022 are outlined by orange polygons and labeled by lake name. The deposits are inferred to be associated with failures triggered by the 1935 Temiscaming earthquake. Also shown is the area west of Temiscaming where surveying is planned for 2023. A yellow-shaded oval encompasses the area within which the 1935 earthquake epicentre is estimated to be located (data from Adams and Vonk, 2009).

Figure 5-4: Preliminary Map of the Young, Subaqueous Landslides Identified in Sub-bottom Acoustic Surveys in the Temiscaming Area.

5.2.4 Geomechanical Stability of the Repository

5.2.4.1 Excavation Damaged Zones

The current EDZ V project led by the Queen’s Geomechanics and Geohazards Group (QGGG) has facilitated advanced EDZ investigation using physical laboratory testing and numerical modelling and has supported 5 doctoral and 5 master’s research students. The EDZ V project focuses on developing predictive tools for Excavation Damage Zone (EDZ) evolution around deep geological repository excavations in sedimentary and crystalline rock, with emphasis on robust and universally applicable EDZ damage threshold definition and updated conventional testing, investigation tools, and numerical approaches. In addition, the EDZ V project is developing techniques to quantify the evolution and impact of damage, including fracture density, propagation, aperture, and connectivity. The following is a summary of the developments by the QGGG on the EDZ V project in 2024.

5.2.4.2 Brazilian Tensile Strength Testing with Acoustic Emissions and Digital Image Correlation

Part of the work in 2024 has been building on the work completed in 2023 to increase the validity and reliability of Brazilian Tensile Strength (BTS) tests for the determination of true tensile strength or TTS (current standard procedures over-predict this measure). The use of lateral strain gauges was previously demonstrated to show “first crack” during the test which correlates directly to the TTS (Packulak et al. 2024). This research had previously also led to a number of suggested improvements to test procedures, sample preparation, and test system compliance thresholds for this very sensitive test (Packulak & Day 2023). Building on this work, BTS test procedures and analysis methods by leveraging AE event detection (that measures damage evolution) (Malicki et al. 2024), as well as 2D digital image correlation (DIC) (that measures temporally and spatially comprehensive strain patterns on BTS specimen faces, with increased accuracy due to numerous procedural improvements, e.g., Packulak et al. 2023) are currently being further advanced. These techniques have set the stage for ongoing work related to tensile strength and crack evolution in heterogeneous rocks (grain scale as well as veined/defected rock) and anisotropic rock with a variety of foliation types.

In 2024, expertise in 3D DIC on BTS specimens as a step toward applying 3D DIC to unconfined compressive strength (UCS) specimens was developed. Currently, significant effort is being invested on solving the challenges of using 2D and 3D DIC to capture small strains measured in low porosity crystalline and sedimentary rocks. This involves careful specimen preparation (Woodland et al. 2023), laboratory equipment setup and calibration (Gagnon et al. 2023), and mathematically rigorous post-processing to properly resolve strain calculations (Gagnon & Day 2024). Applying DIC to generate strain maps of geomechanical laboratory tests is a valuable technique to assess strain and damage evolution, particularly in heterogenous and foliated (gneissic, schistose, or slaty) rock (Packulak et al. 2023).

5.2.4.3 Unconfined Compressive Strength Testing on Isotropic, Anisotropic, and Heated Rocks

For isotropic crystalline igneous and sedimentary rocks, the laboratory investigations on the evolution of elastic parameters including Young’s modulus and Poisson’s ratio reveals changes in these measurements with damage accumulation and with increasing confinement. Robust data analysis procedures for calculation of these parameters are being developed.

In addition, UCS tests on a variety of foliated, transversely isotropic, low porosity rocks were conducted to measure the elastic parameters, brittle damage thresholds, and strength of these geologically complex specimens (Packulak 2024). The role of fabric anisotropy in damage evolution involves both the typical tensile crack development and slip along critically oriented fabric. Consequently, geomechanical laboratory measurement and data analysis of these rocks involves strain measurements and acoustic emissions (AE). The QGGG has recently developed capacity and optimized techniques for investigating the effects of EDZ damage development, coupled with confinement effects, on ultrasonic velocity when under load (McDonald 2023), providing another useful testing tool but also a tool for explaining discrepancies between laboratory-based P and S wave velocities and the in-hole wave velocities in the field (and the stiffness parameters so obtained).

In 2024, a new experimental process for high temperature UCS tests was designed, whereby the specimens are heated prior to the test and insulated for the test duration. This enables measurement of all geomechanical properties in a UCS laboratory setting, with on-specimen strain, AE, and ultrasonic velocity. This will facilitate analysis of the impacts of high temperature exposure of rock on elastic parameters, AE, P and S wave velocities, brittle damage evolution, and peak strength.

5.2.4.4 Direct Shear Laboratory Investigations and Characterization of Fracture Anisotropy

The impacts of fracture anisotropy (including slickensides) and shear direction on shear stiffness and strength are being addressed through laboratory direct shear testing of synthetic replicate specimens that are generated using digital 3D photogrammetry models of real rock fracture surfaces, and 3D printed molds that are used to cast cement grout specimens (MacDonald 2022; Hoyle et al. 2023). Controlled air temperature and relative humidity during the curing process further ensures consistent physical properties of the specimens.

Furthermore, a technique for the graphical presentation and quantification of shear strength anisotropy within the plane of the discontinuity has been developed, for the purpose of incorporating this effect into numerical modelling of surfaces and excavations (Hoyle et al. 2024).

5.2.4.5 Small Strain Monitoring and Model Calibration for Fibre-Optic Extensometers and Instrumented Rock-Support Elements

After creating verification linkages between continuum rockmass damage and yield modelling, and hybrid models incorporating equivalent Discrete Fracture Network (DFN) structure, these models are being used to calibrate conventional linear support of extensometer elements within a variety of numerical approaches, to reproduce the small strain response of support elements in physical testing using embedded fibre optic strain measurement (Fischer & Diederichs 2024). This work is essential for using the support elements for a DGR excavation, for the purpose of small strain EDZ measurement and verification during construction.

5.2.4.6 Discrete Element Method Numerical Modelling of EDZ Damage Development, Dilation, and Confinement Effects for Pillars and Excavations

Advanced numerical modelling is ongoing to explore the internal mechanics of brittle rock in the post-yield (spalling through crushing) regime in granitoids and other related polycrystalline rocks. The results of discrete element simulations (bonded particle models) are being used to inform finite element and finite difference modelling (with or without DFN elements) of brittle EDZ development and ground response for verification modelling.

5.2.4.7 Finite-Discrete Element Method Numerical Modelling of Foliated Rocks

The physical laboratory test data from transversely isotropic foliated rocks are being leveraged to calibrate FDEM numerical models of these tests. The calibrated FDEM models, which are able to simulate fracture propagation, will enable detailed investigation of tensile fractures and shear slip in the models as part of this project going into 2025.

5.2.4.8 Fracture Toughness

A critical literature review of fracture toughness laboratory tests, standards, suggested methods, and the accuracy of data produced from each method has begun in 2024. The results will guide the development of state-of-art fracture toughness approaches for granitic and schistose rock, with a focus on practical and repeatable testing methods based on cylindrical rock core samples. This lays the groundwork for ongoing research to investigate the influence of fracture toughness and stress path on EDZ numerical model parameters.

6 REPOSITORY SAFETY

The objective of the repository safety program is to evaluate the pre-closure and post-closure safety of the deep geological repository.

Previously, the NWMO has completed generic 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). These reports summarized key aspects of the repository concept and explained why the repository concept is expected to be safe in these locations (see Table 6-1). Currently the NWMO is focussed on preliminary safety assessment of a repository at the Revell Site, using site-specific information.

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 3.3 million used CANDU fuel bundles in storage at reactor sites in Canada. 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.

Three scenarios are provided in the estimates of *Nuclear Fuel Waste Projections in Canada – 2024 Update* resulting in a best estimate range of 5.7-6.4 million bundles (Reilly 2024). The reference scenario for projected future total number of used fuel bundles produced by the existing reactor fleet is approximately 5.9 million bundles (113,000 Mg heavy metal), based on published plans for existing CANDU stations as of September 2024. The forecast is subject to potential changes on annual basis, to account for reactor operators’ updated plans for refurbishment and life extension, as well as for adjustments in calculations to reflect the most up-to-date numbers of bundles in storage versus previous year’s projections (Reilly 2024).

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 prototype CANDU fuel bundles 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 in service in low-power research reactors at McMaster University, Royal Military College of Canada, École Polytechnique de Montréal and the

Canadian Nuclear Laboratories (CNL). In 2024, this inventory was reviewed and an interim updated description developed for design and safety consideration.

The Canadian used fuel inventory and forecast are updated annually by the NWMO with the most recent fuel inventory and forecast documented in Reilly (2024).

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 will only be released as the fuel itself dissolves (which in turn will only occur 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. Extensive research was conducted to understand the mechanisms of UO_2 dissolution under used fuel container conditions (the effects of H_2O_2 decomposition (Liu et al. 2017a, 2017b, 2017c, 2017d, 2018, 2019; Zhu et al. 2019, Badley and Shoesmith 2023) and H_2O_2 reduction (Zhu et al. 2020, 2022) on UO_2 dissolution, and the effect of H_2 on suppressing the corrosion behavior of UO_2 (Liu et al. 2021)).

An option for the legacy metallic U and U carbide fuels from the early stage of fuel development is to convert them to a uranium oxide prior to the final geological disposal. Researchers at Western University are characterizing the oxidized U materials and will determine the reactivity of these surfaces in corrosion experiments. ThO_2-based materials containing fissile isotopes (e.g., ^{233}U, ^{235}U or ^{239}Pu) were included in the legacy research fuels, and also are candidates for new nuclear reactor fuels. The dissolution behavior of ThO_2 and mixed $Th_{1-X}U_XO_2$ fuels will be investigated under disposal conditions.

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.

In 2024, the NWMO continued 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). The review of the chemical thermodynamics of selected ancillary compounds of interest to radioactive waste management was completed in 2024 (Rand et al. 2024). The reviews of molybdenum thermodynamic data and the state-of-the-art reports on the thermodynamics of cement materials and high-ionic strength systems (Pitzer model) are underway. Phase VI of the NEA Thermodynamic Database (TDB) project will provide a review of the chemical thermodynamics of lanthanides.

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 was needed for radionuclide solubility calculations for sedimentary rock environment. In 2024, the NWMO further developed the NWMO reference Pitzer thermodynamic database DGR_Pitzer_TDB (Colàs 2022) to increase its accuracy, applicability and transparency, including evaluation of thermodynamic data for the Na-Mg-Ca-K-SO_4 system and the Na-Mg-Ca-K-SO_4-Cl system. The development resulted to a new version of the DGR_Pitzer_TDB version 6.

Most thermodynamic data is at around 25°C. The NWMO is interested in properties up to 100-150°C. The NWMO therefore co-sponsored 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 and progress has been made in several areas: (1) the equilibrium constants for uranyl complexes with sulfate at high salinities from 25 to 350ºC have been determined by Raman spectroscopy approach (Alcorn 2019); (2) the equilibrium constants for uranyl complexes with chloride at high salinities from 25 to 300ºC have been determined by Raman spectroscopy approach (a paper will be submitted in 2025). The results of the research on thermodynamic properties of uranyl chloride complexes have been re-evaluated and refitted to be incorporated into the PHREEQC database; (3) the equilibrium constants and transport properties of lanthanum with chloride at high salinities from 25 to 250ºC have been determined by Raman spectroscopy and conductivity approach (Persaud 2024); 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 (the NEA TDB initial report was completed in 2022). The uranyl chloride work, including the PHREEQC compatible parameters will be published as an MSc thesis and in a journal article in 2025.

6.3 BIOSPHERE

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.

6.3.1 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.

In 2024, the NWMO continued to participate in this forum and sponsored the workshop on biosphere modelling, hosted by Posiva in Turku, Finland. The primary objective of the workshop was to share good practice, including modeling approaches and supporting data. The scope of the workshop included intercomparison of biosphere dose conversion factors, presentations of each participating organisations latest assessment-level biosphere modelling approaches, and a workshop report. The workshop report was published by BIOPROTA in 2024.

6.3.2 Biodiversity Conservation Benefits when Performing Impact Assessments

Research supported by the NWMO at the University of British Columbia’s Centre for Environmental Assessment Research determined ways in which federal impact assessments in Canada can contribute to biodiversity conservation (Laye, 2024). In particular, the study developed a set of principles and practical approaches for considering project-related biodiversity impacts as part of the decision-making process of federal impact assessments. The results demonstrated that through the project impact assessment, a net-positive outcome for biodiversity conservation can be achieved.

6.4 SAFETY ASSESSMENT

6.4.1 Pre-closure Safety

The pre-closure period includes site preparation, construction, operation, monitoring, decommissioning, and closure of the facility. Pre-closure safety assessments include normal operations safety (public and worker dose), and malfunctions and accidents. These topics were addressed for a generic site as part of AECL’s Environmental Impact Statement (AECL 1994, OHN 1994) and reviewed as part of the NWMO options study (NWMO 2005). The NWMO is presently updating the analysis methodology and conducting initial site-based assessments; this work is updated with more site-specific information and design once available.

In 2024, the NWMO developed the methodology for pre-closure safety assessment, to assess the radiological and chemical impacts from the DGR facility during normal operation and in case of potential accident conditions associated with the operation of the facility. The methodology considers impacts to workers at the facility, and to members of the public and non-human biota located near the facility.

6.4.1.1 Acceptance Criteria

Acceptance criteria for radiological and non-radiological contaminants applicable to pre-closure safety assessments are used to judge the acceptability of analysis results for the protection of humans and the environment. In 2024, the NWMO advanced the work on developing preliminary pre-closure criteria for the protection of persons and the environment from radiological and non-radiological contaminants, consistent with the latest applicable national and international guidance.

6.4.1.2 Normal Operations

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

Preliminary pre-closure safety analysis was carried out in 2024, to estimate the potential radiological and chemical impact to workers, the public and non-human biota (plants and animals) from normal operation of the DGR and its related surface processing facilities. A conceptual design of the DGR with potential site-specific surface facility layout was considered 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 elements. Waterborne emissions could result from cell washdowns and decontamination of used fuel modules, used fuel transportation packages, and containers. The analysis considers potential facility emissions (airborne and waterborne) and external exposure (direct and skyshine). Simple conservative models are used to estimate the dispersion of airborne and waterborne emissions, and the external dose from the used fuel in the UFPP. The study assumes exposure to the public and non-human biota (plants and animals) at a several locations near the facility, including a potential fence line location and locations relevant to the lifestyles of the local communities. Workers are assumed to be present in representative locations within the UFPP and the surface facilities, in order to develop an overall understanding of the doses to various worker groups at the DGR facility. The preliminary normal operation analysis indicates that the potential radiological doses would be below the preliminary acceptance criteria for public, workers and non-human biota. This preliminary analysis is continuing to incorporate site specific information and will inform the further development of the preliminary DGR design.

6.4.2 Abnormal Events and Accidents

A preliminary study was carried out in 2016 for a generic site 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).

Potential external natural and human-induced hazard events are dependent on the site. In 2022, the NWMO conducted preliminary assessments to identify the external hazards at the two DGR study areas in Ontario and to screen out hazards that are unlikely to lead to effects on systems, structures, and components at the site. The assessment followed the guidance of REGDOC-2.4.4 (CNSC 2022) and REGDOC-1.1.1 (CNSC 2018).

In 2024, the NWMO initiated site-specific preliminary hazard identifications for both the Revell Site and South Bruce Site. Internal initiating events were identified using the systematic approach described in Reijonen et al. (2016) for internal initiating events associated with the operations in the UFPP and the underground repository. The external hazard assessments conducted in 2022 were used to identify and assess external event scenarios from external initiating events.

Preliminary pre-closure accident assessment was carried out in 2024, including assessing the potential radiological and chemical impact to workers, the public and non-human biota (plants and animals) for several accident scenarios consistent with the identified external and internal hazard assessment completed in 2024. The study assumes exposure to the public and non-human biota (plants and animals) at a several locations near the facility, including a potential fence line location and locations relevant to the lifestyles of the local communities. Workers are assumed to be present in representative locations within the UFPP and the surface facilities. Atmospheric dispersion factors were derived based on the Gaussian dispersion model described in CSA Standard N288.2:19 (CSA 2019). The presence or absence of ventilation system High Efficiency Particulate Air filters is also considered in combination with specific accident scenarios.

The preliminary analysis indicates that the potential public doses for inhalation, air immersion and ground exposure pathways would remain below the preliminary safety assessment acceptance criteria for all accidents considered. This preliminary analysis is continuing to incorporate site specific information.

6.4.2.1 Dose Rate Analysis

Accurate estimates of dose rates associated with different used fuel configurations are required to support the radiological characterization of used fuel during handling. In 2022, two geometry configurations were analysed (an unshielded single used fuel bundle and used fuel bundles inside a UFC), using the latest radionuclide inventory estimates (Heckman and Edward 2020), the latest container design and to include a more detailed representation of the within-bundle source term spatial distribution. Dose rate locations up to 100 m from the source were considered, and calculations were performed for two burnup values (220 MWh/kgU and 290 MWh/kgU) and for decay times up to 10^7 years. The results of this work were published in a technical report (Ariani 2022).

In 2024, the analysis of additional used fuel configurations and the radiological characterization of the used fuel in used fuel containers, transfer casks, transportation packages, buffer boxes, and in various stages in the underground placement rooms was completed.

6.4.2.2 Climate Change Impacts

In 2024, NWMO launched a new site-specific climate change impact study for the Wabigoon Lake Ojibway Nation (WLON) and Ignace area in northwestern Ontario. This study is comprised of two phases of work. The focus of Phase 1 is to perform a comprehensive literature review and develop methods for estimating probable maximum precipitation (PMP), intensity-duration-frequency (IDF), rainfall on snow, and other additional climate variable values (temperature, wind speed, potential evapotranspiration, relative humidity, and drought) under a changing climate. Following the proposed updated methods, PMP, IDF, rainfall on snow, and other additional climate variable values will be estimated in Phase 2 of this study for the WLON and Ignace area. This study is expected to finish in 2025.

6.4.3 Post-closure Safety

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.

6.4.3.1 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. In 2024, the NWMO advanced the work on developing preliminary post-closure criteria for the protection of persons and the environment from radiological and non-radiological contaminants, consistent with the latest applicable national and international guidance.

6.4.3.2 Site-Specific Post-closure Safety Analyses

The post-closure assessment methodology is based on guidance from REGDOC-2.11.1 volume III, version 2 (CNSC 2021b). The 2024 preliminary post-closure safety assessment work focused on advancing the site-specific analyses of the Revell Site.

- Updates to the site-specific post-closure analysis consistent with engineering, geoscience and environmental assessment data available at the end of 2023;
- Refinement and further development of conceptual models of the Revell Site and to the Integrated System Model (see Section 6.4.3.2.1) used to assess repository performance in the post-closure period;
- Refinement of a set of scenarios considered in the post-closure assessment including normal evolution and alternative scenarios (disruptive events, what-if, and human intrusion scenarios).

6.4.3.2.1 Integrated System Model

The NWMO initiated in 2018 the development of a 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 HydroGeoSphere 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 most exposed group and a variety of illustrative receptors living near the repository.

In 2024, the ISM v1.4 was released. As part of ISM v1.4, the wasteform model (ISM-WF) was developed. The ISM-WF model estimates radionuclide and element “source terms” from a variety of wasteforms that may be disposed of in the deep geologic repository (DGR) (e.g., CANDU fuels, prototype fuels and research fuels, and DGR facility generated low level wastes). The wasteform model interfaces with the geosphere model by passing source term fluxes to the geosphere.

As of ISM v1.4, the near-field model (ISM-NF) becomes an optional component as its primary use is replaced by the ISM-WF. The theory of the component models of the initial ISM versions was described in Gobien et al. (2023). Figure 6-1 shows the structure of the ISM component models combined with the data processing and linking tool known as paLINK.

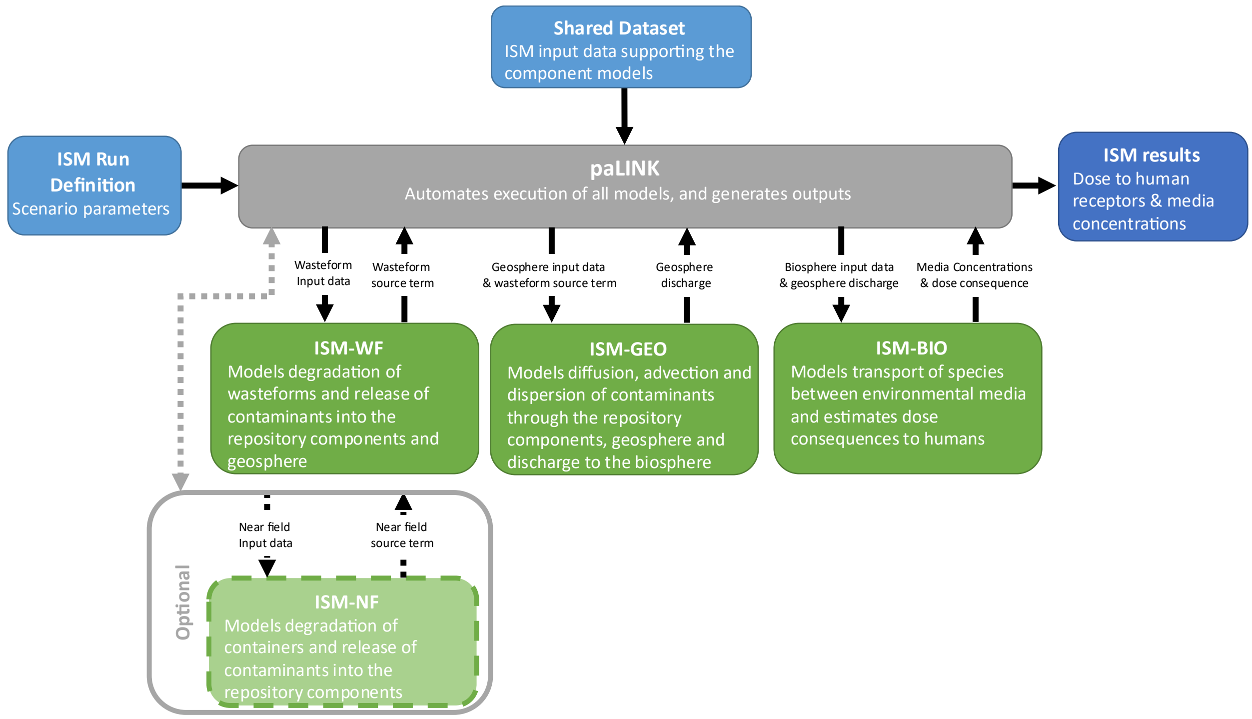


Figure 6-1: paLINK-ISM Configuration

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). 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 4.4.2.2). A preliminary validation report is in development.

6.4.3.3 Thermal Hydraulic Mechanical Response of the Deep Geological Repository

One aspect of the long-term performance is the Thermal-Hydraulic-Mechanical (THM) response of the rock caused by the heat released from the high-level radioactive used fuel placed in the repository. To better understand the coupled process in a DGR, an integrated model was developed to calculate the THM response of a DGR (Guo 2023).

In 2024, an integrated THM model was built to explore the importance of scale in modelling THM response in a crystalline rock. The model included a site-scale domain of rock and representation of the DGR. The DGR panels were represented using large flat blocks with 18 placement rooms modelled explicitly. A portion of one of the 7 placement rooms (the fourth placement room) is represented in detail and includes representation of 14 used fuel containers and the excavation damaged zone surrounding the placement room (see Figure 6-2).

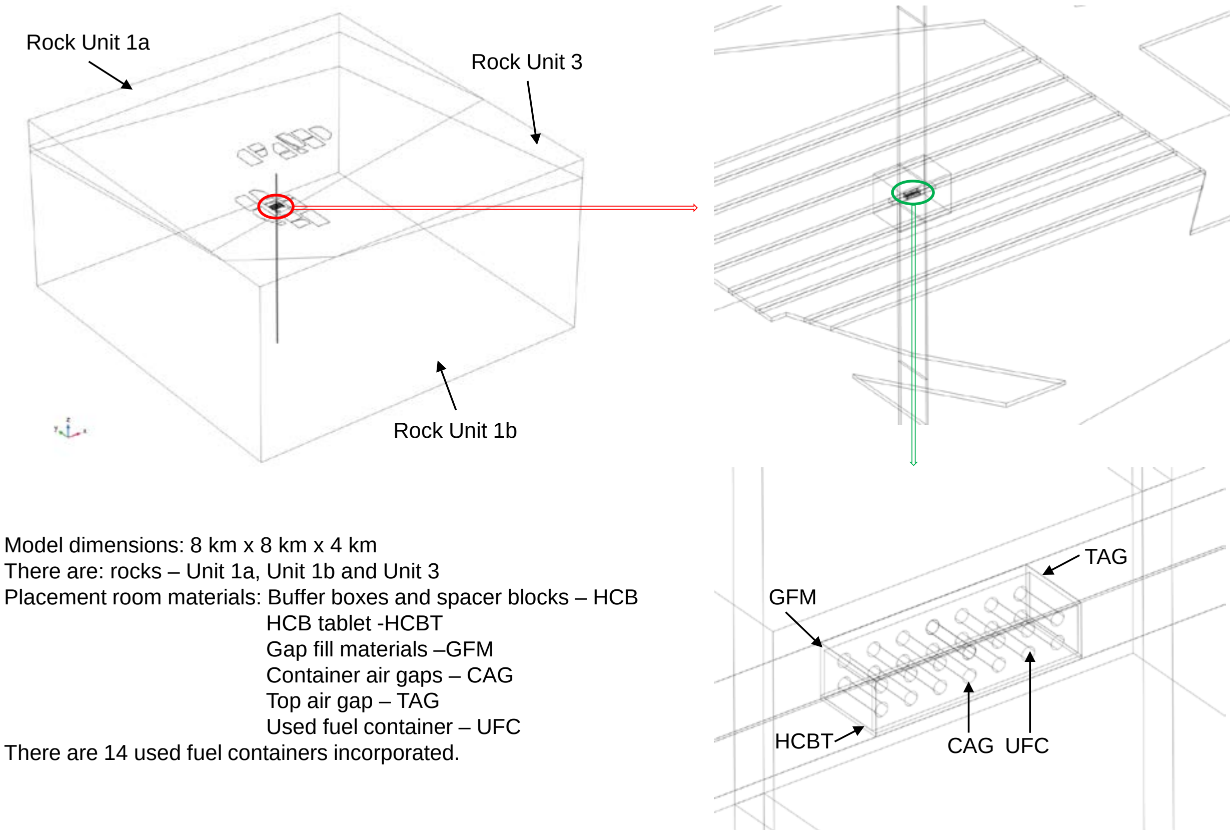
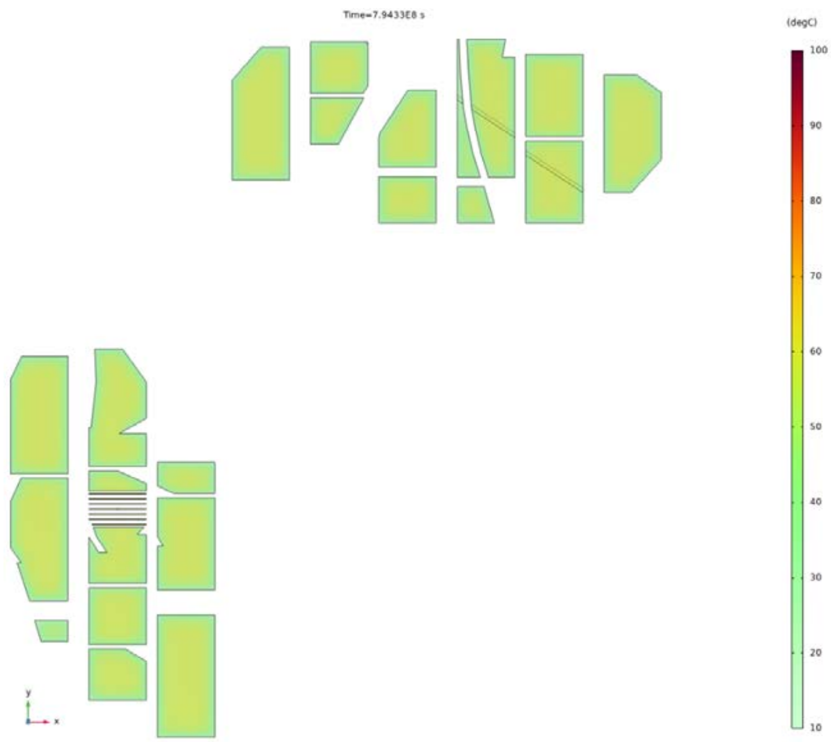


Figure 6-2: Integrated Model Geometry with Seven Placement Rooms in One of Which 14 Containers Are Presented in Detail

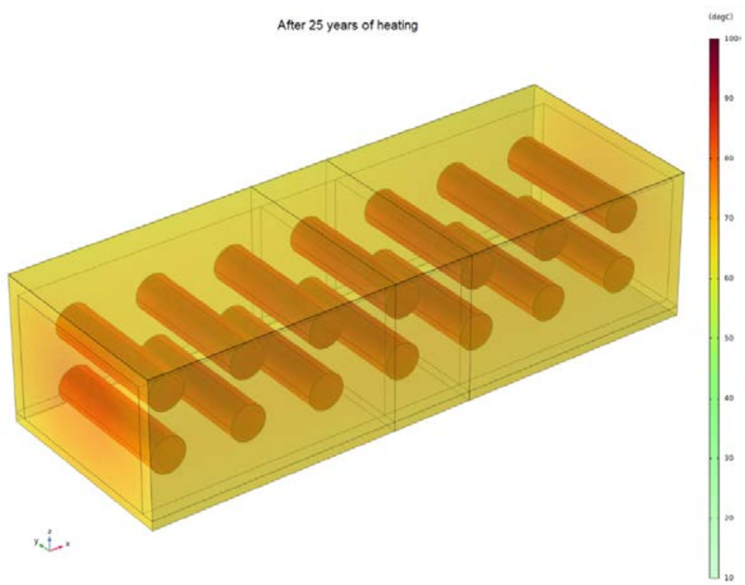
A preliminary study of the THM response of the rock mass around the proposed repository was performed using this model and its results were validated using the method detailed in Guo (2017). In this study, the peak container temperature was 94ºC occurring after about 25 years (Figure 6-3). Thermally-induced pore pressures increase in the rock, generally reaching peaks within 5 years for the first peak (maximum value of 4.5 MPa at the mid-point between two placement room) and 1,800 years for the second peak (8.7 MPa). The maximum stress in the X-direction is 64.6 MPa occurring at 0.5 m from the wall after 45 years. The maximum value of stress in the Y-direction is 73 MPa occurring at 0.5 m from the roof after 63 years. The maximum vertical tensile stress at placement room wall is 1.2 MPa occurring at wall after 45 years, indicating that the wall will be fractured (but this is within the EDZ, as already known to be damaged). The maximum horizontal tensile stress on the ground surface is 6.5 MPa and 5.1 MPa occurring at 3,500 years in the Y- and X-directions, respectively. The maximum depth of the tensile stress is 68 m both in the X- and in the Y-directions. The maximum total pressure acting on the outside surface of the upper layer container is 13 MPa occurring after 1,800 years. Considering glaciation load, the maximum acting stress will increase to 30 MPa at peak glaciation load time

Using constant porosity in coupled THM modelling for the repository in the Revell Site underestimates the pore pressure at early time, but it only has very minor influence on the pore pressure in the long term. Its influence on the thermally-induced stresses and uplift is small enough to be ignored.



Model (GSM).

(a)



(b)

Figure 6-3: Temperatures in Different Panels (a) and in Placement Rooms at Center of Panel 4 (b) after 25 Years of heating from the Coupled THM Integrated Model

Using the as-placed thermal conductivity for the buffer materials gives conservative temperatures at locations in the placement room and has little influence on the temperature in the rock. It also has significant influence on the pore pressures in the placement room and in the rock before the materials in the placement room become fully saturated. Ignoring the saturation process in the coupled THM modelling has some influence on the stress inside rock, but the influence is small enough to be ignored or conservative.

The glaciation influence on the thermal, hydraulic and mechanical response in the repository was also studied..

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 previously completed NEA projects such as the Repository Metadata (RepMet) Management (NEA 2018), and the Preservation of Records, Knowledge and Memory (RK&M) across Generations projects (NEA 2019a, 2019b, 2019c).

The WP-IDKM recently completed a cycle for their last Program of Work (PoW), marking the culmination of efforts, through ongoing research and reporting, by its four sub expert groups:

- EGSSC - Expert Group on a Data and Information Management Strategy for the Safety Case
- EGKM - Expert Group on Knowledge Management for Radioactive Waste Programmes and Decommissioning
- EGAR - Expert Group on Archiving for Radioactive Waste Management Activities
- EGAP – Expert Group on Awareness Preservation after Repository Closure

Including identifying sets of essential records (SER), how to physically archive these SERs, what should appear in a key information file (KIF) as well as the relationship between the SER and the KIF.

The NWMO continues to participate in the WP-IDKM annual general meeting and workshops.

7 SITE ASSESSMENT

In 2024, the NWMO continued to assess the suitability of both potential sites: the WLON-Ignace area in northwestern Ontario, and the SON-South Bruce area in southern Ontario, as the siting decision was not made until the end of the year. The status of the geological and environmental studies underway in these regions is described below.

7.1 WABIGOON LAKE OJIBWAY NATION (WLON) AND IGNACE AREA

7.1.1 Geological Investigation

By the end of 2023, the majority of Geoscience fieldwork activities for this phase of work were completed. Monitoring of the previously installed shallow groundwater network (Figure 7-1) and the microseismic network were the main field activities still on-going. Desktop review and finalization of data deliverables, and technical reports, from field and laboratory programs was a key priority. In 2024, key activities supported the advancement of site understanding based on the analysis and integration of data from the field and laboratory programs. Some on-going initiatives included, refinement of the site-scale geological model, initiation of site-specific in situ stress modelling and long-term geomechanical stability analysis, and assessment of site-specific groundwater and porewater composition. All of these activities will support the future development of hydrogeological flow and transport models.

Figure 7-1: Installed shallow groundwater monitoring well in the Wabigoon Lake Ojibway Nation and Ignace Area.

NWMO’s Confidence in Safety – Wabigoon Lake Ojibway Nation and Ignace area (NWMO, 2023c) report was released at the end of Q1 2024, summarizing the results as of mid-2023 indicating that this site would be suitable from a technical perspective for hosting a repository. It was intended to support public discussion around site selection. Additionally, an assessment of any potential resources at the Revell site indicated that the site has extremely low mineral potential and is unlikely to change for hundreds of thousands of years into the future (Wilson, 2024).

7.1.2 Environmental Program

A key piece of work completed in the Northwest for 2024 included the completion of Year 3 of the environmental media baseline monitoring and further bat research. Additionally, the Year 2 Environmental Media Baseline Report was publicly released.

Baseline media work completed in 2024 included: surface water quality monitoring, hydrology, atmospheric studies, aquatic and terrestrial tissue sampling. To complete this work the NWMO contracted KGS Group as the environmental baseline data collection consultant. Ongoing engagement related to the environment program, and environmental monitoring of site investigation studies also continued. Details of the work completed in 2024 are described below.

7.1.2.1 Atmospheric Monitoring

In 2023, Year 1 of the air quality monitoring portion of the overall atmospheric work was started in the Northwest. Field consultants continued to return monthly in 2024 to complete sampling at the main station (Figure 7-2) and the three Local Study Area (LSA) dust fall samplers deployed in the Area of Interest (AOI). Sampling at the main station includes continuous, passive, and active sampling methods while sampling at the LSA stations is passive.

Figure 7-2: Photo Showing the Main Site Study Area (SSA) Atmospheric Monitoring Trailer.

7.1.2.2 Aquatic and Terrestrial Tissue Chemistry

In 2024, the aquatic and terrestrial tissue chemistry portion of the Environmental Media Baseline Program (EMBP) was started in the Northwest. Field consultants, in partnership with Wabigoon Lake Ojibway Nation community members, conducted one aquatic tissue sampling event and 5 terrestrial tissue sampling field events. During the aquatic sampling event field crews visited multiple locations on two waterbodies and one watercourse within the LSA to collect large- and small-bodied fish, aquatic plants, and sediment. A total of 130 aquatic tissue samples were collected during this field event. During the terrestrial sampling events field crews visited various locations within the local and regional study areas to collect terrestrial insects and vegetation including berries and mushrooms, and co-located soil samples. A total of 296 terrestrial tissue samples were collected during these five field events.

The NWMO also launched a donation-based tissue sampling program in 2024. Based on input received from workshops, and an expressed willingness to donate samples of vegetation, fish and wildlife to the Environmental Media Baseline Program for laboratory analysis, the Community Sampling Program was implemented. In exchange for tissue samples donated towards this program, the NWMO has 11 community designed crests (Figure 7-3) available for collection by participants. The crest received will be based on the type of wildlife or vegetation donated. In 2024, a total of seven samples of moose were donated by hunters for laboratory analysis.

Figure 7-3: Community Designed Crests to be Given to Participants Donating a Tissue Sample to the NWMO's Community Sampling Program.

7.1.2.3 Bat Research in Partnership with the Toronto Zoo

The NWMO has continued its partnership 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 2024 included continued passive acoustic monitoring of bats at eight locations on and around the Revell and Ignace area, and ten nights of mist netting surveys to capture bats (Figure 7-4). Capture surveys yielded 9 captured bats of two species across three sites: four silver-haired bats and five endangered little brown myotis.

Youth engagement was another factor included in the bat program work in 2024. Youth from Wabigoon Lake Ojibway Nation joined Toronto Zoo Native Bat Conservation program representatives and NWMO staff in the field for one day mini bat camp. Toronto Zoo staff gave a presentation on bats and bat conservation. The youth attending learned how to set up the survey equipment and how bats are captured, observed and data recorded, and then safely released. In the evening, participants helped set-up two mist nets and conducted checks on the nets every 15 minutes. Participants were able to gain hands-on experience using bat monitoring equipment and spend the night in the field participating in all aspects of bat capture and release surveys. Toronto Zoo Native Bat Conservation program representatives also attended the Second Northwest Nuclear Exploration Event hosted in Ignace, Ontario. An information booth highlighting key information on the program, bats in Ontario and the work being done was set-up in the main exhibitor area. Toronto Zoo staff also delivered three presentations to youth from local schools educating participants on bats in Ontario and the threats they face.

Figure 7-4: Photo from an Evening Field Monitoring Session in the WLON-Ignace Area. The Little Brown Myotis is Displaying Typical Behaviour When Handled by Opening Their Mouth to Echolocate and Gain an Understanding of What is Going on. Photo Taken in July 2024 by Toronto Zoo.

7.1.2.4 Surface Water Quality and Hydrology

In 2024, surface water quality monitoring was completed in partnership with Wabigoon Lake Ojibway Nation community members. During the three seasonal campaigns a total of 69 sites were visited and 210 samples collected. Hydrology monitoring was also continued in 2024 and included lake level monitoring at nine lake and pond sites, flow monitoring at seven stream and river sites, and telemetry at two sites.

7.1.2.5 Engagement

Engagement related to the environmental program is ongoing in the Northwest. In 2024 this included representation at community events such as open houses and providing information and environmental work updates to various community groups. Two environmental day camps were also held for youth in the Ignace community. Participants accompanied an NWMO environment staff person in the field and spent the day identifying different trees, plants and wildlife. Day camp participants also built their own terrariums to take home afterwards.

NWMO environment staff and representatives from Canada North Environmental Services, KGS Group, LGL Ltd., North/South Consultants, Scatliff + Miller + Murray and Zoetica Environmental Consulting attended the two-day long Northwest Nuclear Exploration Event in the community of Ignace. During the event two environment program booths were set up to showcase the programs being run in the Northwest and to allow visitors to ask NWMO, program designers and field staff questions about the work and any results that had been found so far (Figure 7-5).

Figure 7-5: NWMO Environment Program and Field Consultant Staff at the Northwest Nuclear Exploration Event in Ignace, Ontario, April 2024.

7.1.2.6 Planned 2025 Work

Following the Site Selection announcement that WLON-Ignace will host the Deep Geological Repository, going forward into 2025 the environmental baseline monitoring program will continue in the Northwest. Work will include the continuation of atmospheric monitoring (air quality, noise, and light), hydrology studies, and further surface water quality sampling. Additional Tier 2 studies will also be implemented in 2025 including fish and bird surveys. 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.

7.2 SAUGEEN OJIBWAY NATION (SON)-SOUTH BRUCE AREA

7.2.1 Geological Investigation

In 2024, the majority of Geoscience fieldwork activities for this phase of work were completed. Maintenance and monitoring of the previously installed shallow groundwater network and the microseismic network were the main field activities still on-going. Desktop review and finalization of data deliverables, and technical reports, from field and laboratory programs was a key priority.

NWMO's Confidence in Safety – Saugeen Ojibway Nation - South Bruce area (NWMO, 2023b) report was released at the end of Q1 2024, summarizing the results as of mid-2023 indicating that this site would be suitable from a technical perspective for hosting a repository. It was intended to support public discussion around site selection. Following the decision to site the DGR at the Revell site, any further activities at the South Bruce site are not contemplated.

7.2.2 Environmental Program

Environmental field work in the SON-South Bruce area completed in 2024 included the surface water, hydrology, surficial soil and atmospheric components of the Environmental Media Baseline Program (EMBP), as well as terrestrial ecosystem mapping, aquatic habitat mapping, and environmental DNA (eDNA) gap filling work as part of the Biodiversity Impact Studies. Ongoing engagement related to the environment program, and field level oversight also continued. Public release of reporting related to field work completed in 2024 is expected in 2025. Details of the work completed in 2024 are described below.

7.2.2.1 Surface Water Quality and Hydrology

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

As part of this program, the SVCA completed the surface water quality component of the EMBP in the SON-South Bruce area. The SVCA completed the 2024 winter and spring sampling campaigns at 34 sites throughout the Saugeen watershed (Figure 7-6). Spring 2024 marked the completion of Year 3 data collection. Field sampling for the EMBP included phytoplankton, zooplankton, and periphyton, in addition to surface water quality sampling.

The SVCA also continued the hydrology component of the EMBP, including monthly water level measurements, maintenance of two flow stations along the Teeswater River collecting continuous water level data, maintenance of a meteorological station in the Area of Interest (AOI) collecting continuous weather information, and characterization of the Teeswater River following the Ontario Stream Assessment Protocol (OSAP).

Results from Year 2 of the surface water and hydrology programs (completed fall 2022-summer 2023) were published in November 2024 (CanNorth et al., 2024).

Figure 7-6: SVCA Staff Collecting Water Samples in Lake Huron, May 2024

7.2.2.2 Surficial Soil Sampling

As part of the NWMO's environmental media baseline program, TULLOCH Environmental (TULLOCH) was contracted to complete surficial soil sampling (Figure 7-7).

Figure 7-7: Surficial Soil Samples in Laboratory Supplied Containers, September 2024.

Land permissions were obtained before entry to private properties. In September 2024, TULLOCH collected samples from 6 locations to quality check results of samples collected in 2023, to increase spatial coverage, and to increase sample collection from different land uses. Results from Year 1 of the surficial soil program (completed in August 2023) were published in November 2024 (CanNorth et al., 2024).

7.2.2.3 Atmospheric Program

Calian Ltd. was contracted to complete the atmospheric component of the Environmental Media Baseline Program. In summer 2024, an atmospheric monitoring station was commissioned at the Borehole 1 location (Figure 7-8). Sampling at the monitoring station includes continuous, passive, and active methods.

Figure 7-8: Atmospheric Monitoring Station at Borehole 1

7.2.2.4 Aquatic Habitat Mapping

Aquatic habitat mapping was completed in spring and summer of 2024 to fill data gaps identified in the 2022 dataset. The 2024 program focused on revisiting sites that were dry in summer 2022 during spring 2024 in attempt to map those areas while they contained seasonal water, as well as to visit new sites in summer 2024 on private properties that were not previously accessible. Field crews from North South Consultants and Morrison Hershfield visited 102 sites in the spring and 37 sites in the summer of 2024.

7.2.2.5 Environmental DNA

Environmental DNA (eDNA) sampling was completed by North South Consultants at watercourses, wetlands, and waterbodies in the SON-South Bruce area in spring, summer, and fall of 2024. Sites that were previously visited in 2022 were revisited, with the goal of collecting eDNA from each site once in each seasonal window. New sites were also visited on private properties that were not accessible in 2022 to expand upon the eDNA sampling spatial coverage. eDNA samples were collected from 156 sites in spring 2024, 38 sites in summer 2024 and 14 sites in fall 2024.

The NWMO and the University of Guelph have partnered on a joint eDNA research program. eDNA is a non-invasive technology used to detect potential species presence by looking at DNA that is naturally shed by animals and studying the collected DNA using metabarcoding technology. Once samples are collected in the field by NWMO's consultants (Figure 7-9), they are sent to the University of Guelph's Hanner Lab for analysis and interpretation to help understand what species are likely to be present in the local environment based on existing genetic sequence libraries.

Figure 7-9: Filter paper after passes through OSMOS sampler. The filter paper is extracted using sterile tweezers and sent to Hanner Lab at the University of Guelph. Photo was taken in April 2024 by North/South Consultants.

7.2.2.6 Terrestrial Ecosystem Mapping and Significant Wildlife Habitat Identification

Terrestrial ecosystem mapping and significant wildlife habitat identification was completed by TULLOCH Environmental, and subconsultants from Natural Resources Solutions Incorporated and Insight Environmental at 144 sites in the SON-South Bruce area during summer 2024. The summer 2024 program was aimed to expand the spatial distribution of the work that was undertaken in 2022, with particular focus on surveying the southern portion of the local study area.

7.2.2.7 Planned 2025 Work

Given the Site Selection announcement that WLON-Ignace will host the Deep Geological Repository, there will be no further environmental field programs in SON-South Bruce. Reporting on data collected up to the end of 2024 will also be published in 2025 and equipment installed in the field will be decommissioned.

REFERENCES

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.

Adams J., Vonk A. 2009. The November 1, 1935, M 6.2 Timiskaming earthquake, its aftershocks, and subsequent seismicity. Geological Survey of Canada, Open File 6207, 65 pp.

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.S., R. Crowe, M Tortola – 2021. Dolomitization of Paleozoic Successions, Huron Domain of Southern Ontario, Canada: Fluid Flow and Dolomite Evolution. Water 2021, 13, 2449

Al-Aasm, I., R. Crowe, M. Tortola and M. Ozyurt. 2023. Diagenetic evolution of secondary evaporites and associated host rock dolostones in the Huron Domain (Michigan Basin): Insights from petrography, geochemistry, and C-O-S-Sr isotopes. Journal of Sedimentary Research. https://doi.org/10.2110/jsr.2023.102

Alcorn, C.D., J.S. Cox, Lucas M.S.G.A. Applegarth and P.R. Tremaine. 2019. Investigation of Uranyl Sulfate Complexation under Hydrothermal Conditions by Quantitative Raman Spectroscopy and Density Functional Theory The Journal of Physical Chemistry B, Volume 123, Issue 34, August 29, 2019. Pages 7241-7490.

Ariani, I. 2022. Dose Rate Analysis to Support Radiological Characterization of Used CANDU Fuel. Nuclear Waste Management Organization Technical Report NWMO-TR-2022-03. Toronto, Canada.

Badley, M. and D.W. Shoesmith. 2022. The Corrosion/Dissolution of Used Nuclear Fuel in a Deep Geological Repository. Nuclear Waste Management Organization Technical Report NWMO-TR-2022-09. Toronto, Canada.

Badley, M., D.W. Shoesmith and J.J. Noël. 2023. Effect of hydrogen on the dissolution of uranium dioxide in peroxide-containing environments. Journal of the Electrochemical Society 170, 096506. DOI: 10.1149/1945-7111/acf52b.

Badley, M. 2024. The characterization and electrochemistry of natural uranium dioxide under long-term disposal conditions. PhD thesis. The University of Western Ontario. London, Ontario, Canada.

Behazin, M. Briggs, S. King, F. 2023 Radiation-induced corrosion model for copper-coated used fuel containers. Part 1. Validation of the bulk radiolysis submodel. Materials Corrosion. https://doi.org/10.1002/maco.202313770

Beaver, R.C., K. Engel, W.J. Binns and J.D. Neufeld. 2022. Microbiology of barrier component analogues of a deep geological repository. Can. J. Microbiol. 68: 73–90 (2022).

dx.doi.org/10.1139/cjm-2021-0225 Published at www.cdnsciencepub.com/cjm on 14 October 2021.73

Beaver RC, Vachon MA, Tully CS, Engel K, Spasov E, Binns WJ, Noël JJ, Neufeld JD. Impact of dry density and incomplete saturation on microbial growth in bentonite clay for nuclear waste storage. J Appl Microbiol. 2024 Mar 1;135(3):lxae053. doi: 10.1093/jambio/lxae053. PMID: 38458234.eaver et al 2024

Beaver, R. 2024. Microbiology of bentonite clay relevant to a deep geological repository for used nuclear fuel. PhD thesis, University of Waterloo, Waterloo, Ontario, Canada.

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. https://doi.org/10.1016/j.ijrmms.2019.03.015.

Boumaiza, L., Stotler, R. and Frape, S. 2024. A review of the major chemical and isotopic characteristics of groundwater in crystalline rocks of the Canadian Shield. Chemical Geology 669, 122366. https://doi.org/10.1016/j.chemgeo.2024.122366

Briggs, S.; Behazin, M.; King, F. Numerical Implementation of Mixed-Potential Model for Copper Corrosion in a Deep Geological Repository Environment.; Sheraton Fallsview, Niagara Falls, ON, Canada, August 27 2023.

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

Brooks, G. R. 2024. A major paleoearthquake in central Canada interpreted from early postglacial subaqueous mass transport deposits. Past Global Changes Magazine, 32(1), 08-09.

CanNorth, Geosyntec, and SVCA. 2024. Saugeen Ojibway Nation-South Bruce Area Environmental Media Baseline Program – Year 2 Baseline Report. APM-REP-07000-0243.

Chen, J., Z. Qin. L. Wu, J.J. Noël, and D.W. Shoesmith. 2014. The influence of sulphide transport on the growth and properties of copper sulphide films on copper. Corros. Sci. 87, 233-238.

Chen, J., Z. Qin, T. Martino, and D.W. Shoesmith. 2017. Effect of chloride on Cu corrosion in anaerobic sulphide solutions. Corros. Eng. Sci. Technol. 52:sup1, 40-44.

Chowdhury, F., T.L. Rashwan, P. Mondal, M. Behazin, P.G. Keech, J.S. Sharma, M. Krol. 2024, Effect of compaction on bisulfide diffusive transport through MX-80 bentonite, Journal of Contaminant Hydrology, 264, 104341.

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. 2018. Reactor Facilities Site Evaluation and Site Preparation for New Reactor Facilities. Canadian Nuclear Safety Commission, REGDOC-1.1.1. Ottawa, Canada.

CNSC. 2021a. REGDOC-2.11.2. Waste Management Decommissioning., Ottawa, Canada.

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

CNSC. 2022. Safety Analysis for Class IB Nuclear Facilities. Canadian Nuclear Safety Commission, REGDOC-2.4.4. Ottawa, Canada.

CSA. 2016. Quality Assurance of Analytical, Scientific, and Design Computer Programs. CSA Standard N286.7-16 (R2021). Toronto, Canada.

CSA. 2019. Guidelines for Calculating Radiation Consequences to the Public of a Release of Airborne Radioactive Material for Nuclear Reactors Accidents. Canadian Standards Association CSA N288.2:19 (R2024). 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.

Colàs, E., O. Riba, A. Valls, D. García and L. Duro. 2022. Radionuclide Solubility Calculations (Phase 2). Nuclear Waste Management Organization Technical Report NWMO-TR-2022-11. Toronto, Canada.

Damiani, L.H., G. Kosakowski, A. Vinsot and S.V. Churakov. 2022. Hydrogen gas transfer between a borehole and claystone: experiment and geological model. Environmental Geomechanics, 1-14. https://doi.org/10.1680/jenge.21.00061

Darcel, C., Le Goc, R., Lavoine, E., Davy, P., Mas Ivars, D., Sykes, E., Kasani, H.A. 2024. Coupling stress and transmissivity to define equivalent directional hydraulic conductivity of fractured rocks. Engineering Geology 342, 107739. https://doi.org/10.1016/j.enggeo.2024.107739

Doughty, M., Eyles, N., & Daurio, L. (2010). Ongoing Neotectonic Activity in the Timiskaming – Kipawa Area of Ontario and Québec. *Geoscience Canada*, *37*(3). Retrieved from https://journals.lib.unb.ca/index.php/GC/article/view/18397

Engel K., S. Coyotzi, M.A. Vachon, J.R. McKelvie and J.D. Neufeld. 2019. Validating DNA Extraction Protocols for Bentonite Clay. mSphere 4(5). doi: 10.1128/mSphere.00334-19.

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

Esefelder, R., Wawerzinek, B., Lüth, S., Giese, R. & Krawczyk, C.M. (2021). Seismic anisotropy of Opalinus Clay: tomographic investigations using the infrastructure of an underground rock laboratory (URL). Swiss J Geosci 114, 21. https://doi.org/10.1186/s00015-021-00398-2.

Fischer CP, Diederichs MS. 2024. Elasto-Plastic and Post-Yield Weakening Jointed Rockmass Response in a Comparison of Equivalent-Continuum and Explicit Structural Models. Canadian Geotechnical Journal, 61(4): 611-626. https://doi.org/10.1139/cgj-2022-0190

Fosu, B.R., J.J. Jautzy, W. Yong and R.A. Secco. 2023. Introducing the “Franken-Kiel” carbonate device: first application to Δ_{47}T calibration of calcite and dolomite. Geochemistry, Geophysics, Geosystems, 24, e2023GC011047. https://doi.org/10.1029/2023GC011047.

Gagnon É, Day JJ. 2024. The practicality of quality assessment metrics for millimeter-scale digital image correlation speckle patterns. Strain, 61(1), e12491(2025): 20p. https://doi.org/10.1111/str.12491

Gagnon É, Packulak TRM, Woodland SK, Diederichs MS, Day JJ. 2023. Challenges and solutions of 2D Digital Image Correlation for Brazilian Tensile Strength testing on hard rock. In Proc. GeoSaskatoon, Bridging Infrastructure and Resources, 76th Canadian Geotechnical Society Annual Conference, Saskatoon, SK, Canada, 1-4 October.

Gobien, M., S. Briggs, A. Boyer, J. Avis, and N. Calder. 2023. Overview of the Integrated System Model. 5th Canadian Conference on Nuclear Waste Management, Decommissioning and Environmental Restoration. Niagara Falls, Canada. Aug 27-31, 2023.

Graupner B, K. Thatcher, R. Newson, AA. Chaudhry, C. Lee, CH. Park, D. Naumov, E. Matteo, H. Shao, JT. Kim, J. Thiedau, J. Rutqvist, J. Buchwald, L. Friedenberg, M. Bjorge, M. Pitz, P.-Z. Pan, R. Guo, S. Kaiser, T. Hadgu, T. Dewers, T. Nagel, W. Hou, W. Wang and W. Rühaak. 2024. *Final Report of Task C – DECOVLAEX-2023*. Lawrance National Laboratory report - 2001623; 2024.

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.

Guglielmi, Y., Nussbaum, C., Cappa, F., De Barros, L., Rutqvist, J. and Birkholzer, J., 2021. Field-scale fault reactivation experiments by fluid injection highlight aseismic leakage in caprock analogs: Implications for CO2 sequestration. International Journal of Greenhouse Gas Control, 111, p.103471.

Guo, M., J. Chen, T. Martino, M. Biesinger, J.J. Noël, and D.W. Shoesmith. 2019. The susceptibility of copper to pitting corrosion in borate-buffered aqueous solutions containing chloride and sulfide. J. Electrochem. Soc. 166, C550-C558.

Guo, M., J. Chen, T. Martino, C. Lilja, J.A. Johansson, M. Behazin, W.J. Binns, P.G. Keech, J.J. Noël, and D.W. Shoesmith. 2020. The nature of the copper sulfide film grown on copper in aqueous sulfide and chloride solutions. Mater. Corros. doi.org:1.1002/maco.202011710.

Guo, R. 2017. Thermal response of a Canadian conceptual deep geological repository in crystalline rock and a method to correct the influence of the near-field adiabatic boundary condition. Engineering Geology 2017; 218: 50-62. http://dx.doi.org/10.1016/j.enggeo.2016.12.014.

Guo, R. 2023. Calculation of thermal-hydraulic-mechanical response of a deep geological repository for radioactive used fuel in granite. International Journal of Rock Mechanics and Mining Sciences 170 (2023) 105435. https://doi.org/10.1016/j.ijrmms.2023.105435.

Guo R. and S. Briggs. 2024. Thermo-hydro-mechanical calibration modelling of the full-scale emplacement experiment and sensitivity analyses. International Journal of Rock Mechanics and Mining Sciences. 186 (2025) 106031. https://doi.org/10.1016/j.ijrmms.2025.106031.

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.

Hoyle WR, MacDonald NR, Day JJ, Diederichs MS. 2023. Laboratory investigation on the effect of roughness anisotropy on shear strength of rock fractures. In Proc. GeoSaskatoon, Bridging Infrastructure and Resources, 76th Canadian Geotechnical Society Annual Conference, Saskatoon, SK, Canada, 1-4 October.

Hoyle W, Packulak TRM, Diederichs MS, Day JJ. 2024. Development of kinematic analysis for shear of anisotropic rock fracture surfaces. Nuclear Waste Management Organization, NWMO, Geoscience Seminar, Toronto, ON, June 4-5 [poster].

Huo, J., A.P.S. Selvadurai, M. Meguid. 2024. Permeability Evolution in a Fracture in Granite During Isotropic Compression. Rock Mechanics and Rock Engineering, 57, 6511–6525. https://doi.org/10.1007/s00603-024-03875-w

Jacobsson, L.,J. Larsson, M., Flansbjer, D. Mas-Ivars. H.A. Kasani, F. Johansson, F. 2024. Mechanical properties of large rock cracks. Foundation for Rock Engineering Research BeFo:s, Bergdagarna 2024, Stockholm Sweden (In Swedish).

Jacobsson L., J. Larsson, M. Flansbjer, D. Mas-Ivars, H.A. Kasani, F. Johansson. 2024. Mekaniska egenskaper hos stora bergsprickor, Bergdagarna 2024, Stockholm Sweden (in Swedish)

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, D. Mas Ivars, H.A. Kasani. 2024a. A method for quantifying uncertainty in stress domain boundaries. EUROCK 2024: ISRM European Symposium on New Challenges in Rock Mechanics and Rock Engineering, Alicante, Spain.

Javaid, M.A., J.P. Harrison, H.A. Kasani, D. Mas Ivars. 2024b. An examination of the correlation properties of variable in situ stress in rocks for developing informative priors. GeoMontreal 2024: Canadian Geotechnical Society Conference on Resilient geosciences for future generations, Montreal, Quebec, Canada.

Javaid, M.A., J.P. Harrison. 2024. Enhanced statistical analysis of in situ stress data. Poster presented at the NWMO Annual Geoscience Seminar 2024, Toronto, Ontario, Canada.

King, F., J. Chen, Z. Qin, D. Shoesmith, and C. Lilja. 2017. Sulphide-transport control of the corrosion of copper canisters. Corros. Eng. Sci. Technol. 52:sup1, 210-216.

King, F. and M. Behazin. 2021. A Review of the Effect of Irradiation on the Corrosion of Copper-Coated Used Fuel Containers. Corrosion and Materials Degradation, 2, 678–707.

Kong, D., C. Dong, A. Xu, C. Man, C. He, and X. Li. 2017a. Effect of sulfide concentration on copper corrosion in anoxic chloride-containing solutions. J. Mater. Eng. Performance 26, 1741-1750.

Kong, D., A. Xu, C. Dong, F. Mao, K. Xiao, X. Li, and D.D. Macdonald. 2017b. Electrochemical investigation and *ab initio* computation of passive film properties on copper in anaerobic sulphide solutions. Corros. Sci. 116, 34-43.

Lavoine E, C. Darcel P. Davy, D. Mas Ivars, H. Kasani. 2024. Rock mass strength properties from a DFN approach. Proceedings of Eurocks 2024, Alicante, July 15-19, 2024.

Laye, Evan. 2024. Principles for the practical consideration of biodiversity within Canadian impact assessment processes under the Impact Assessment Act. M. Sc. Thesis. University of British Columbia. Vancouver. Canada.

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., H. He, J.J. Noël and D.W. Shoesmith. 2017b. 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. 2017c. 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. 2017d. 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.

Longstaffe, F.J., Cassidy, C., Klyn-Hesselink, H., Struminski-Bodden, A., Asadi Mehmandosti, E. and Kennell, L. (2024) Can clay-water isotopic exchange and bound water-mobile water fractionations affect measured shale porewater isotopic compositions? Workshop on Porewater Chemistry of Clayrocks in Repository Environments. Edited by Paul

Wersin et al. NEA/NSC/R (2024) draft, Centre de Meuse, Centre de Meuse/Haute Marne, Bure, France, June 12-14, 2024.

MacDonald N.R. 2022. A critical laboratory investigation of multi-stage direct shear testing procedures on rock joints using synthetic replica specimens. MASc Thesis, Department of Geological Sciences and Geological Engineering, Queen's University, Kingston, Ontario, Canada. Available from: http://hdl.handle.net/1974/30277

Malicki EM, Packulak TRM, Gagnon É, Diederichs MS, Day JJ. 2024. Measuring brittle damage thresholds of crystalline rocks by acoustic emissions on compressive and tensile laboratory tests. 58th US Rock Mechanics / Geomechanics Symposium, American Rock Mechanics Association, Golden, CO, USA.

Malmir. M., J. Molson and R. Therrien. 2024. Numerical modelling of permafrost-impacted groundwater flow systems in the context of a deep geological repository. 12th International Conference on Permafrost. 16-20 June 2024, Whitehorse, Canada.

Malmberg, D., O. Kristensson and A. Spetz. 2024. THM Modelling of the Bentonite Buffer During Water Uptake for NWMO's Emplacement Room. Clay Technology Lund AB on contract to the Nuclear Waste Management Organization. Technical Report NWMO-TR-2024-05. Toronto, Ontario, Canada.

Martino, T., R. Partovi-Nia, J. Chen, Z. Qin, and D.W. Shoesmith. 2014. Mechanisms of film growth on copper in aqueous solutions containing sulphide and chloride under voltammetric conditions. Electrochim. Acta 127, 439-447.

Martino, T., J. Chen, Z. Qin, and D.W. Shoesmith. 2017. The kinetics of film growth and their influence on the susceptibility to pitting of copper in aqueous sulphide solutions. Corros. Eng. Sci. Technol., 52:sup1, 61-64.

Martino, T., J. Smith, J. Chen, Z. Qin, J.J. Noël, and D.W. Shoesmith. 2019a. The properties of electrochemically-grown copper sulfide films. J. Electrochem. Soc. 166, C9-C18.

Martino, T., J. Chen, M. Guo, S. Ramamurthy, D.W. Shoesmith, and J.J. Noël. 2019b. Comments on E. Huttunen-Saarivirta et al., 'Kinetic Properties of the Passive Film on Copper in the Presence of Sulfate-Reducing Bacteria", J. Electrochem. Soc. 165(9) (2018) C450-C460. J. Electrochem. Soc. 166, Y13-Y16.

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

Müller HR, B. Garitte, T. Vogt1, S. Köhler, T. Sakaki, H. Weber, T. Spillmann, M. Hertrich,·JK. Becker, N. Giroud, V. Cloet, N. Diomidis and T. Vietor. 2017. Implementation of the full-scale emplacement (FE) experiment at the Mont Terri rock laboratory. Swiss J Geosci. 2017; 110:287–306. DOI 10.1007/s00015-016-0251-2.

Nagasaki, S., Z. Zheng, J. Liu, J. Yang, T. Yang. 2024a. Sorption of Tc(IV) in saline solutions – I. Sorption on MX-80 and granite in Ca-Na-Cl solutions. Journal of Nuclear Fuel Cycle and Waste Technology 22(3), 273-285. https://doi.org/10.7733/jnfcwt.2024.028

Nagasaki, S., Z. Zheng, J. Liu, J. Yang, T. Yang. 2024b. Sorption of Tc(IV) in saline solutions – II. Sorption on MX-80, illite, shale and limestone in Na-Ca-Cl solutions. Journal of Nuclear Fuel Cycle and Waste Technology 22(3), 287-289. https://doi.org/10.7733/jnfcwt.2024.027

Nagasaki, S. 2024c. Sorption Properties of Se(-II) and Tc(IV) on MX-80 Bentonite, Illite, Shale, and Limestone in Na-Ca-Cl Solutions, and on MX-80 Bentonite and Granite in Ca-Na-Cl Solutions. The Nuclear Waste Management Organization Technical Report NWMO-TR-2024-06. Toronto, Canada.

Nagasaki, S. 2024b. Sorption Testing for Revell Site (5 Core Samples) for Ag, Cd, Cs, I, Pb, Pd, Sb, Sn, Sr, Zr, Mo, Rh, Cr and U. The Nuclear Waste Management Organization Technical Report NWMO-TR-2024-07. Toronto, Canada.

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

Najem, T. Zal, D. Blume, O., Sobhia, L., Potvin, J., Landry, M. and I. Clark. 2024. Application of Vacuum-Distillation for Porewater Extraction from Crystalline Rock Samples: Method Development and Benchmarking. NWMO-TR-2024-04. Toronto, Canada.

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 Used Nuclear Fuel. 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 2017. Postclosure Safety Assessment of a Used Fuel Repository in Crystalline Rock. Nuclear Waste Management Organization. NWMO-TR-2017-02. 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. Characterization of Optimized Low Heat High Performance Concrete. Nuclear Waste Management Organization Technical Report NWMO-TR-2021-20. 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 2022. Technical Program for Long-Term Management of Canada's Used Nuclear Fuel - Annual Report 2021. Ed. S. Briggs. Nuclear Waste Management Organization Technical Report NWMO-TR-2022-01. Toronto, Canada.

NWMO 2023a. Technical Program for Long-Term Management of Canada's Used Nuclear Fuel - Annual Report 2022. Ed. S. Briggs. Nuclear Waste Management Organization Technical Report NWMO-TR-2023-01. Toronto, Canada.

NWMO 2023b. Confidence in Safety – South Bruce Site - 2023 Update. Nuclear Waste Management Organization Technical Report NWMO-TR-2023-08. Toronto, Canada.

NWMO 2023c. Confidence in Safety – Revell Site - 2023 Update. Nuclear Waste Management Organization Technical Report NWMO-TR-2023-07. Toronto, Canada.

NWMO 2024. Implementing Adaptive Phased Management 2024-2028. 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 TRM. 2024. Enhanced laboratory testing and characterization related to the mechanics of anisotropic rock. PhD Thesis, Department of Geological Sciences and Geological Engineering, Queen's University, Kingston, Ontario, Canada. Available from: https://hdl.handle.net/1974/32843

Packulak TRM, Day JJ, McDonald MR, Jacksteit AC, Diederichs MS. 2024a. Measurement of true tensile strength from Brazilian tensile strength laboratory tests. Canadian Geotechnical Journal, 62:1-14(2025). https://doi.org/10.1139/cgj-2023-0204

Packulak TRM, Day JJ. 2023. The impact of axial load distribution on Brazilian tensile testing on rock. Rock Mechanics and Rock Engineering, 57: 979–991(2024). https://doi.org/10.1007/s00603-023-03583-x

Packulak TRM, Gagnon É, Woodland SK, Day JJ. 2023. Application of digital image correlation for analysis of anisotropic materials under tension. 15th International ISRM Congress & 72nd Geomechanics Colloquium: Challenges in Rock Mechanics & Rock Engineering, Salzburg, Austria, 9-14 Oct.

Papry, S.A., Rashwan, T.L., Mondal, P.K., Behazin, M., Keech, P.G., Krol, M.M. 2023. Investigating bisulfide sorption onto bentonite through laboratory batch experiments. Applied Geochemistry 152, 105626.

Persaud, A.A., S. Sasidharanpillai, J.S. Cox and P.R. Tremaine. 2024. Speciation and formation constants of aqueous lanthanum(III) chloride complexes from 5 to 80°C by Raman spectroscopy. Canadian Journal of Chemistry 102, 922-934.

Petersen, N. J., ,J. McKenzie, B. Kurylyk, J. Chen: 2022. Numerical modeling investigations of hydrologic regime shifts during permafrost transition periods (Wolf Creek catchment, Yukon). Halifax 2022. Annual Geological Association of Canada Conference. Halifax Convention Centre, Halifax, Nova Scotia, Canada.

Plampin, M.R. and Provost, A.M. 2022. Possible effects of multiphase methane evolution during a glacial cycle on underpressure development in sedimentary basins: An analysis with application to the northeast Michigan Basin. Journal of Geophysical Research: Solid Earth, 127 e2021JB023322. https://doi.org/10.1029/2021JB023322.

Racette, J., A. Walker, S. Nagasaki, T. Yang, T. Saito and P. Vilks. 2023. Influence of Ca-N-Cl physicochemical solution properties on the adsorption of Se(-II) onto granite and MX-80 bentonite. Nuclear Engineering and Technology 55, 3831-3843.

Rand, W., D.A. Palmer, J. Fuger and T. Gajda. 2024. Chemical thermodynamics of Selected Ancillary Compounds of Interest to Radioactive Waste Management. Ed by Martinez, J.S., M-E, Ragoussi and D. Costa. OECD NEA, Boulogne-Billancourt, France.

Rashwan, T.L., Md. Abdullah Asad, Ian L. Molnar, Mehran Behazin, Peter G. Keech, Magdalena M. Krol, 2023. Exploring the governing transport mechanisms of corrosive agents in a Canadian deep geological repository, Science of The Total Environment, 828, 153944.

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.

Reilly, T. 2024. Nuclear Fuel Waste Projections in Canada – 2024 Update. Nuclear Waste Management Organization Technical Report NWMO-TR-2024-09. Toronto, Canada.

Salonen, T., T. Lamminmäki, F. King, and B. Pastina. 2021. Status report of the Finnish spent fuel geologic repository programme and ongoing corrosion studies. Mater. Corros. doi.org:1.1002/maco.202011805.

Saxena Nishtha, Emmanuel Mena-Morcillo, Mia Tripp, Peter George Keech, Mehran Behazin, and Samantha Michelle Gateman. 2024, ACS Measurement Science Au 0, *0*, pp DOI: 10.1021/acsmeasuresciau.4c00042

Seyedi D.M., Plua C., Vite I.M., et al. Upscaling TH M modelling from small -scale to full -scale in -situ experiments in the Callovo -Oxfordian claystone . Int J Rock Mech Min Sci . 2021 ;14 4 :104582 . https://doi.org/10.1016/j.ijrmms.2020.104582

Situm, A,. M. Sabeti, N. Schmidt, D. Zagidulin, M. Behazin, J. J. Noël. 2024. Monitoring alterations in a salt layer's deliquescence properties during the atmospheric corrosion of a metal surface using a quartz crystal microbalance, Corrosion Science, 229, 2024, 111845.

Smith, J., Z. Qin. F. King, L. Werme, and D.W. Shoesmith. 2007. Sulfide film formation on copper under electrochemical and natural corrosion conditions. Corrosion 63, 135-144.

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

Steffen, H and R. Steffen. 2024. Temporal Behavior of Glacially Induced Stresses and Strains at Potential Sites for Long-Term Storage of Used Nuclear Fuel in Canada. Journal Geological Research : Earth Surface, 129. https://doi.org/10.1029/2024JF007705 .

Stuhne, G. and W.R. Peltier. 2023. Surface Boundary Conditions During Long-Term Climate Change Simulated by the UofTGSM 2.0 Framework. Nuclear Waste Management Organization Technical Report NWMO-TR-2023-10. Toronto, Canada.

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.

Su, D., K.U. Mayer and K.T.B. MacQuarrie. 2022. Implementation of 2D/3D-unstructured Grid Capabilities into MIN3P-THCm, Nuclear Waste Management Organization Technical Report NWMO-TR-2022-10. Toronto, Canada.

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).

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. 2022. Sorption of Se(-II) on Illite, MX-80 Bentonite, Shale, and Limestone in Na-Ca-Cl Solutions. Nuclear Engineering and Technology 54 (5), 1616-1622.

Wawerzinek, B., Esefelder, R., Giese, R., Jurczyk, A., Krawczyk, C., Krüger, K., Lueth, S. (2022a): Seismic pilot survey in the Mont Terri Underground Rock Laboratory. Switzerland (URL)https://doi.org/10.5880/GIPP.201999.1

Wawerzinek, B., Esefelder, R., Giese, R., Jurczyk, A., Krawczyk, C., Krüger, K., Lueth, S. (2022b): Seismic repeat survey acquired in the Mont Terri Underground Rock Laboratory (URL), Switzerland. https://doi.org/10.5880/GIPP.202099.1.

Wawerzinek, B., Lueth, S., Esefelder, R., Giese, R., Krawczyk, C. (2022c): Performance of high-resolution impact and vibration sources for underground seismic exploration of clay formations at the scale of a rock laboratory. Geophysical Journal International, 231, 3, ggac283. https://doi.org/10.1093/gji/ggac283.

Wersin, P., Mazurek, M., Gimmi, T. 2022. Porewater chemistry of Opalinus Clay revisited: Findings from 25 years of data collection at the Mont Terri Rock Laboratory. Applied Geochemistry 138, 105234.

Winkelmann, R., Martin, M. A., Haseloff, M., Albrecht, T., Bueler, E., Khroulev, C., and Levermann, A. 2011. The Potsdam Parallel Ice Sheet Model (PISM-PIK) – Part 1: Model Description, The Cryosphere, 5, 715–726, https://doi.org/10.5194/tc-5-715-2011,

Wilson, N. 2024. Future Mineral Resource Potential of the Revell Site. Nuclear Waste Management Organization. NWMO-TR-2024-03. Toronto. Canada.

Woodland SK, Gagnon É, Packulak TRM, Dobosz A, Day JJ. 2023. Paint speckle application recommendations for digital image correlation analysis of Brazilian tensile strength tests on low-porosity rocks. Rock Mechanics and Rock Engineering, 57: 1495–1507(2024). https://doi.org/10.1007/s00603-023-03604-9

Yang, J., J. Racette, F.G. Garcia, S. Nagasaki and T. Yang. 2022. Sorption of Eu on MX-80 bentonite in Na-Ca-Cl brine solutions. Journal of Nuclear Fuel Cycle and Waste Technology 20 (2), 151-160.

Yang, T. and Kennell-Morrison, L. (2021) Reference Porewater Composition SR-290-PW. Nuclear Waste Management Organization, NWMO-TM-03420-T10, 8 p.

You, C., Y. Chuai, S.A. Briggs, and M.E. Orazem. 2024. Model for corrosion of copper in a nuclear waste repository. Corrosion Science, 226, p.111658.

Zappone A., A.P. Rinald, M. Grab, Q. Wenning, C. Roques, C. Madonna, A. Obermann, S. M. Bernasconi , F. Soom, P. Cook, Y. Guglielmi, C. Nussbaum, D. Giardini, S. Wiemer.2020. Fault sealing and caprock integrity for CO2 storage: an in-situ injection experiment. Preprint Solid Earth, https://doi.org/10.5194/se-2020-100, Published Solid Earth, *12*(2), 319‑343. https://doi.org/10.5194/se-12-319-2021.

Zheng, Z., J. Liu, S. Nagasaki, T. Yang. 2024a. Sorption of U(VI) on MX-80 bentonite, illite, shale and limestone in Na-Ca-Cl saline solutions. Nuclear Engineering and Technology 56(11), 4724-4733. https://doi.org/10.1016/j.net.2024.06.036.

Zheng, Z., F.G. Guido Garcia, J. Liu, S. Nagasaki and T. Yang. 2024b. Sorption of U(VI) on MX-80 bentonite and granite in Ca-Na-Cl saline solutions. Nuclear Technology. DOI: 10.1080/00295450.2023.2300900.

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.

Zhu, Z, M. Ly, N. Liu, J.J. Noël and D.W. Shoesmith. 2022. The kinetics of hydrogen peroxide reduction on rare earth doped UO2 and SIMFUEL. Frontiers in Materials 9:1038310. doi: 10.3389/fmats.2022.1038310

APPENDIX A: NWMO TECHNICAL REPORTS AND REFEREED JOURNAL ARTICLES

A.1 NWMO TECHNICAL REPORTS 2024

Boucher, C., N. Ackerley and M. Adams. 2024. Seismic Activity in the Northern Ontario Portion of the Canadian Shield: Annual Progress Report for the Period January 01, 2022 – December 31, 2023. Nuclear Waste Management Organization. Technical Report NWMO-TR-2024-10. Toronto. Canada.

Freire-Canosa, J,. ed. 2024. Technical Program for Long-Term Management of Canada's Used Nuclear Fuel - Annual Report 2023. Nuclear Waste Management Organization Technical Report NWMO-TR-2024-01. Toronto, Canada.

Nagasaki, S. 2024a. Sorption Properties of Se(-II) and Tc(IV) on MX-80 Bentonite, Illite, Shale, and Limestone in Na-Ca-Cl Solutions, and on MX-80 Bentonite and Granite in Ca-Na-Cl Solutions. The Nuclear Waste Management Organization Technical Report NWMO-TR-2024-06. Toronto, Canada.

Nagasaki, S. 2024b. Sorption Testing for Revell Site (5 Core Samples) for Ag, Cd, Cs, I, Pb, Pd, Sb, Sn, Sr, Zr, Mo, Rh, Cr and U. The Nuclear Waste Management Organization Technical Report NWMO-TR-2024-07. Toronto, Canada.

Reilly, T. 2024. Nuclear Fuel Waste Projections in Canada – 2024 Update. Nuclear Waste Management Organization Technical Report NWMO-TR-2024-09. Toronto, Canada

Wilson, N. 2024. Future Mineral Resource Potential of the Revell Site. Nuclear Waste Management Organization. NWMO-TR-2024-03. Toronto. Canada.

.

A.2 REFEREED JOURNAL ARTICLES 2024

Beaver RC, Vachon MA, Tully CS, Engel K, Spasov E, Binns WJ, Noël JJ, Neufeld JD. Impact of dry density and incomplete saturation on microbial growth in bentonite clay for nuclear waste storage. J Appl Microbiol. 2024 Mar 1;135(3):lxae053. doi: 10.1093/jambio/lxae053. PMID: 38458234.

Brooks, G. 2024. A Major Paleoearthquake in Central Canada Interpreted from Early Postglacial Subaqueous Mass Transport Deposits. 2024. Past Global Changes (PAGES). doi.org/10.22498/pages.32.1.8.

Brooks, G., Grenier, A. and Brewer, K., 2024. An investigation of subaqueous failures triggered by the 1935 CE Mw 6.1 Temiscaming earthquake, Quebec, Canada, as an analogue for a paleoseismic study. Canadian Journal of Earth Sciences, V. 61, No. 12, https://doi.org/10.1139/cjes-2024-0080.

Chowdhury, F., T.L. Rashwan, P. Mondal, M. Behazin, P.G. Keech, J.S. Sharma, M. Krol. 2024. Effect of compaction on bisulfide diffusive transport through MX-80 bentonite, Journal of Contaminant Hydrology, 264, 104341.

Darcel, C., Le Goc, R., Lavoine, E., Davy, P., Mas Ivars, D., Sykes, E., Kasani, H.A. 2024. Coupling stress and transmissivity to define equivalent directional hydraulic conductivity of fractured rocks. Engineering Geology 342, 107739. https://doi.org/10.1016/j.enggeo.2024.107739

De Simone, S, C. Darcel, H. Kasani, D Mas Ivars. 2024. The impact of size-dependent and stress-dependent fracture properties on the Biot and Skempton coefficients of fractured rock. Rock Mechanics and Rock Engineering. https://doi.org/10.1007/s00603-024-04038-7

.

Fischer CP, Diederichs MS. 2024. Elasto-Plastic and Post-Yield Weakening Jointed Rockmass Response in a Comparison of Equivalent-Continuum and Explicit Structural Models. Canadian Geotechnical Journal, 61(4): 611-626. https://doi.org/10.1139/cgj-2022-0190

Gagnon É, Day JJ. 2024. The practicality of quality assessment metrics for millimeter-scale digital image correlation speckle patterns. Strain, 61(1), e12491(2025): 20p. https://doi.org/10.1111/str.12491

Guo R. and S. Briggs. 2024. Thermo-hydro-mechanical calibration modelling of the full-scale emplacement experiment and sensitivity analyses. International Journal of Rock Mechanics and Mining Sciences. 186 (2025) 106031. https://doi.org/10.1016/j.ijrmms.2025.106031.

Huo, J., A.P.S. Selvadurai, M. Meguid. 2024. Permeability Evolution in a Fracture in Granite During Isotropic Compression. Rock Mechanics and Rock Engineering, 57, 6511–6525. https://doi.org/10.1007/s00603-024-03875-w

King, F.; Kolàř, M.; Briggs, S.; Behazin, M.; Keech, P.; Diomidis. 2024. N. Review of the Modelling of Corrosion Processes and Lifetime Prediction for HLW/SF Containers—Part 1: Process Models. *Corros. Mater. Degrad. 5*, 124-199. https://doi.org/10.3390/cmd5020007

King, F.; Kolàř, M.; Briggs, S.; Behazin, M.; Keech, P.; Diomidis. 2024. N. Review of the Modelling of Corrosion Processes and Lifetime Prediction for HLW/SF Containers—Part 2: Performance Assessment Models. *Corros. Mater. Degrad. 5*, 289-339. https://doi.org/10.3390/cmd5020013

Kotsakis, I., D. Poirier, J.D. Giallonardo and S. Yue. 2024. “Influence of Feedstock Powder Characteristics on the Response to Heat Treatment of Cold Sprayed Copper Coatings”, Journal of Thermal Spray Technology. https://doi.org/10.1007/s11666-024-01865-6

Mena-Morcillo, E., Ebrahimzadeh Pilehrood, A., Moshrefi R., Shafiee G., Keech P.G., Behazin M., and Gateman, S. 2024. Analytical Chemistry 96 (22), 9122-9131,DOI: 10.1021/acs.analchem.4c00683

Meiling Man, Huan Tong, Nivetha Srikanthan, Muhammed O. Usman, Claire S. Tully, James J. Noël, Mehran Behazin, W. Jeffrey Binns, Peter G. Keech, Myrna J. Simpson. 2024. Analysis of natural organic matter chemistry in bentonite clay under compaction using different dry densities and duration, Applied Geochemistry, 166, 105985.

Nagasaki, S., Z. Zheng, J. Liu, J. Yang, T. Yang. 2024a. Sorption of Tc(IV) in saline solutions – I. Sorption on MX-80 and granite in Ca-Na-Cl solutions. Journal of Nuclear Fuel Cycle and Waste Technology 22(3), 273-285. https://doi.org/10.7733/jnfcwt.2024.028

Nagasaki, S., Z. Zheng, J. Liu, J. Yang, T. Yang. 2024b. Sorption of Tc(IV) in saline solutions – II. Sorption on MX-80, illite, shale and limestone in Na-Ca-Cl solutions. Journal of Nuclear Fuel Cycle and Waste Technology 22(3), 287-289. https://doi.org/10.7733/jnfcwt.2024.027

Neurauter, C.M. James, Nivetha Srikanthan, Huan Tong, Mehran Behazin, Myrna J. Simpson. 2024. Characterization of natural organic matter in Wyoming-type bentonites irradiated at varied moisture levels, Applied Geochemistry,170, 106083,

Persaud, A.A., S. Sasidharanpillai, J.S. Cox and P.R. Tremaine. 2024. Speciation and formation constants of aqueous lanthanum(III) chloride complexes from 5 to 80°C by Raman spectroscopy. Canadian Journal of Chemistry 102, 922-934.

Packulak TRM, Day JJ, McDonald MR, Jacksteit AC, Diederichs MS. 2024. Measurement of true tensile strength from Brazilian tensile strength laboratory tests. Canadian Geotechnical Journal, 62:1-14(2025). https://doi.org/10.1139/cgj-2023-0204

Ramamurthy, S., J Chen, D Zagidulin, JD Henderson, C Lilja, E Bergendal, M Behazin, N Diomidis, PG Keech, JJ Noël, DW Shoesmith. 2024. The influences of traces of oxygen and sulfide on the corrosion of copper in concentrated chloride solutions, Corrosion Science, 233, 112047.

Saxena, Nishtha, Emmanuel Mena-Morcillo, Mia Tripp, Peter George Keech, Mehran Behazin, and Samantha Michelle Gateman. 2024. In Situ Quantification of a Wetted Surface Area during Scanning Electrochemical Cell Microscopy Using Retraction Curves, ACS Measurement Science Au 0, 0, pp. DOI: 10.1021/acsmeasuresciau.4c00042

Situm, A,. M. Sabeti, N. Schmidt, D. Zagidulin, M. Behazin, J. J. Noël. 2024. Monitoring alterations in a salt layer's deliquescence properties during the atmospheric corrosion of a metal surface using a quartz crystal microbalance, Corrosion Science, 229, 2024, 111845.

Steffen, H and R. Steffen. 2024. Temporal Behavior of Glacially Induced Stresses and Strains at Potential Sites for Long-Term Storage of Used Nuclear Fuel in Canada. Journal Geological Research : Earth Surface, 129. https://doi.org/10.1029/2024JF007705 .

Williams D., A. Riahi, A. Carcea, J.D. Giallonardo, P. Keech, S.Y. Persaud, M.R. Daymond, R.C. Newman. 2024. "Hydrogen Embrittlement and Strain Rate Sensitivity of Electrodeposited Copper: Part I – The Effect of Hydrogen Content, npj Materials Degradation, (2024)8:79.

Woodland SK, Gagnon É, Packulak TRM, Dobosz A, Day JJ. 2023. Paint speckle application recommendations for digital image correlation analysis of Brazilian tensile strength tests on low-porosity rocks. Rock Mechanics and Rock Engineering, 57: 1495–1507(2024). https://doi.org/10.1007/s00603-023-03604-9

You, C., Y. Chuai, S.A. Briggs, and M.E. Orazem. 2024. Model for corrosion of copper in a nuclear waste repository. Corrosion Science, 226, p.111658.

Zheng, L., M.J.R. Haché, D. Poirier, J.-G. Legoux, J.D. Giallonardo, Y. Zou, J. Howe and U. Erb. 2024. "Submicrometer Scale Mapping of Microstructure and Mechanical Properties of Cold Sprayed Copper", Journal of Materials Science & Engineering A 920 (2025) 147556.

Zheng, L., D. Poirier, J.-G. Legoux, J.D. Giallonardo, J.Y. Howe and U. Erb. 2024. "Microstructural Characterization of Interfaces between Cold Sprayed Copper and Electrodeposited Copper Corrosion Barrier Coatings for Used Nuclear Fuel Containers", Surface & Coatings Technology, Vol. 494 (2024), p. 131396.

Zheng, Z., J. Liu, S. Nagasaki, T. Yang. 2024. Sorption of U(VI) on MX-80 bentonite, illite, shale and limestone in Na-Ca-Cl saline solutions. Nuclear Engineering and Technology 56(11), 4724-4733. https://doi.org/10.1016/j.net.2024.06.036.

Zheng, Z., F.G. Garcia, J. Liu, S. Nagasaki, T. Yang. 2024. Sorption of U(VI) on MX-80 and granite in Ca-Na-Cl saline solutions. Nuclear Technology 210, 1475-1486. https://doi.org/10.1080/00295450.2023.2300900.

A.3 CONFERENCES PAPERS 2024

Chuai, Y., Briggs, S.A. and Orazem, M.E., 2024, November. A Parametric Study of Mathematical Model for Long-Term Localized Corrosion of Copper in Canadian Deep Geological Repository. In *Electrochemical Society Meeting Abstracts prime2024* (No. 17, pp. 1701-1701). The Electrochemical Society, Inc.

Colàs E., T. Yang, O. Riba, J. Rodríguez-Mestres, P.F. dos Santos, D. Garcia, L. Duro. 2024. “Radionuclides solubility assessment for highly saline groundwaters and database development of DGR-Pitzer-TDB”. 10th International Conference on Nuclear and Radiochemistry – NRC10, August 25-30, 2024, Brighton, UK.

Gobien, M. 2024. Development of a Site-Specific Safety Case for a Canadian Deep Geological Repository for Used Fuel. Proceedings NEA IGSC Safety Case Symposium 2024. Mercure Budapest Castle Hill, Budapest, Hungary, October 8-11, 2024.

Hackett, B.D.C., K. Daub, J.D. Giallonardo, N. Senior, J.D. Henderson, S.Y. Persaud. 2024. “Corrosion of Cold Sprayed Copper in a Gaseous Hydrogen Sulfide Environment”, 43rd Annual CNS Conference and the 48th Annual CNS/CNA Student Conference Sheraton Cavalier Saskatoon Hotel, Saskatoon, SK, Canada, June 16-19, 2024

Hoyle WR, MacDonald NR, Day JJ, Diederichs MS. 2023. Laboratory investigation on the effect of roughness anisotropy on shear strength of rock fractures. In Proc. GeoSaskatoon, Bridging Infrastructure and Resources, 76th Canadian Geotechnical Society Annual Conference, Saskatoon, SK, Canada, 1-4 October.

Jacobsson L., J. Larsson, M. Flansbjer, D. Mas-Ivars, H.A. Kasani, F. Johansson. 2024. Mekaniska egenskaper hos stora bergsprickor, Bergdagarna 2024, Stockholm Sweden (in Swedish)

Javaid, M.A., J.P. Harrison, D. Mas Ivars, H.A. Kasani. 2024a. A method for quantifying uncertainty in stress domain boundaries. EUROCK 2024: ISRM European Symposium on New Challenges in Rock Mechanics and Rock Engineering, Alicante, Spain.

Javaid, M.A., J.P. Harrison, H.A. Kasani, D. Mas Ivars. 2024b. An examination of the correlation properties of variable in situ stress in rocks for developing informative priors. GeoMontreal 2024: Canadian Geotechnical Society Conference on Resilient geosciences for future generations, Montreal, Quebec, Canada.

Javaid, M.A., J.P. Harrison. 2024. Enhanced statistical analysis of in situ stress data. Poster presented at the NWMO Annual Geoscience Seminar 2024, Toronto, Ontario, Canada.

Lavoine E, C. Darcel P. Davy, D. Mas Ivars, H. Kasani. 2024. Rock mass strength properties from a DFN approach. Proceedings of Eurocks 2024, Alicante, July 15-19, 2024.

Liu, K., S. Tsushima, T. Yang, S. Nagasaki. Investigation of Pd(II) sorption onto montmorillonite in a saline environment: a DFT study. Proceedings of 43rd Annual CNS Conference and the 48th Annual CNS/CNA Student Conference, Sheraton Cavalier Saskatoon Hotel, Saskatoon, SK, Canada, June 16-19, 2024.

Liu, K., S. Tsushima, T. Yang, S. Nagasaki. Investigation of Pd(II) sorption onto montmorillonite in a saline environment: a DFT study. Proceedings 5th University of Toronto, University of Tokyo, University McMaster Student Workshop. Hamilton and Toronto, Ontario, Canada, May 14-17, 2024.

Liu, J., S. Nagasaki, and T. Yang. Sorption of Eu(III) onto MX-80 bentonite in Ca-Na-Cl solutions. Proceedings 5th University of Toronto, University of Tokyo and University McMaster Student Workshop. Hamilton and Toronto, Ontario, Canada, May 14-17, 2024.

Longstaffe, F.J., Cassidy, C., Klyn-Hesselink, H., Struminski-Bodden, A., Asadi Mehmandosti, E. and Kennell, L. (2024) Can clay-water isotopic exchange and bound water-mobile water fractionations affect measured shale porewater isotopic compositions? Workshop on Porewater Chemistry of Clayrocks in Repository Environments. Edited by Paul Wersin et al. NEA/NSC/R (2024) draft, Centre de Meuse, Centre de Meuse/Haute Marne, Bure, France, June 12-14, 2024.

Malicki EM, Packulak TRM, Gagnon É, Diederichs MS, Day JJ. 2024. Measuring brittle damage thresholds of crystalline rocks by acoustic emissions on compressive and tensile laboratory tests. 58th US Rock Mechanics / Geomechanics Symposium, American Rock Mechanics Association, Golden, CO, USA.

Papry, Sifat Azad, Tarek L Rashwan, Pulin Mondal, Mehran Behazin, Peter G Keech, Magdalena Krol. 2024. Investigating Bisulphide Sorption onto Bentonite: Methodology Development and Design of Batch, Proceedings of the Canadian Society for Civil Engineering Annual Conference 2023, Volume 8: Environmental Track.

Pilehrood, Ali Ebrahimzadeh, Ghazal Shafiee, Mehran Behazin, Peter George Keech, Samantha Michelle Gateman. 2024.The Effect of Surface Preparation on the Corrosion Behaviour of Copper Coatings, Conference of Metallurgists, 389-396.

Stopelli, E., Guillemot, T., Agnel, M., Briggs, S., King, F., Kipfer, R., Norris, S., Diomidis, N. and Gaus, I., 2024. *FE-G: Gas dynamics over 10 years at the Full-Scale Emplacement experiment (Mont Terri, CH)* (No. EGU24-7345). Copernicus Meetings.

Yang, J., S. Nagasaki, S. Tsushima, T. Yang. The application of DFT and PHREEQC calculation to study sorption mechanisms of Se(-II) on biotite in reducing conditions. Proceedings 5th University of Toronto, University of Tokyo and University McMaster Student Workshop. Hamilton and Toronto, Ontario, Canada, May 14-17, 2024.

Yang, J., S. Nagasaki, S. Tsushima, T. Yang. The DFT study of sorption mechanisms of Se(-II) on biotite in reducing conditions. Proceedings of 43rd Annual CNS Conference and the 48th Annual CNS/CNA Student Conference, Sheraton Cavalier Saskatoon Hotel, Saskatoon, SK, Canada, June 16-19, 2024.

Yang, T., S. Nagasaki, A. Blyth, M. Gobien. 2024. NWMO sorption program overview – sorption of selected radionuclides on Canadian sedimentary and crystalline rocks. Proceedings of the Workshop of Sorption Data Management and Database Development for Radioactive Waste Management Workshop, Barcelona, Spain, September 16-17, 2024.