Technical Program for Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2023

NWMO-TR-2024-01 May 2024

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

NUCLEAR WASTE MANAGEMENT ORGANIZATION
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ABSTRACT

Title: **Technical Program for the Long-Term Management of Canada's Used Nuclear Fuel – Annual Report 2023**
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Abstract

This report is a summary of activities and progress in 2023 for the Nuclear Waste Management Organization's Technical Program. The primary purpose of the Technical Program is to support the implementation of Adaptive Phased Management (APM), Canada's approach for the long-term management of used nuclear fuel.

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

NWMO continued to participate in international research activities, including projects associated with Posiva Encapsulation Plant for spent nuclear fuel, the Mont Terri Underground Rock Laboratory, the SKB Äspö Hard 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 14 NWMO technical reports, published 36 journal articles and presented 23 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.

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

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

The NWMO is presently in the Site Selection phase. No site has been selected to host the DGR. The process for selecting a site is described in *Moving Forward Together: Process for Selecting a Site for Canada’s Deep Geological Repository for Used Nuclear Fuel* (NWMO 2010). The steps for evaluating the geological suitability of willing and informed host communities consists of a) initial screenings to evaluate the suitability of candidate sites against a list of preliminary screening criteria, using readily available information; b) preliminary assessments to further determine if candidate sites may be suitable for developing a safe used fuel repository; and c) detailed field investigations to confirm suitability of one site.

Initially, 22 communities had expressed interest in the program. By 2022 the number of areas engaged in the site selection process had been narrowed to two, the Revell Site in the Wabigoon Lake Ojibway Nation (WLON)-Ignace area and the South Bruce site in the Saugeen Ojibway Nation (SON)-South Bruce area, based on preliminary assessments of potential geological suitability and potential for the project to contribute to community well-being. The location of these potential sites is shown in Figure 1-2. Reports documenting the site selection process to date are available on the NWMO website. https://www.nwmo.ca/Documents-and-reports

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 2023. In the near term, this information will support selection of a preferred site, anticipated to be selected in 2024. In the longer term, this will support an impact assessment and licence applications at the selected site. NWMO’s overall implementation plan is described in *Implementing Adaptive Phased Management* 2023-2027 (NWMO 2023b).

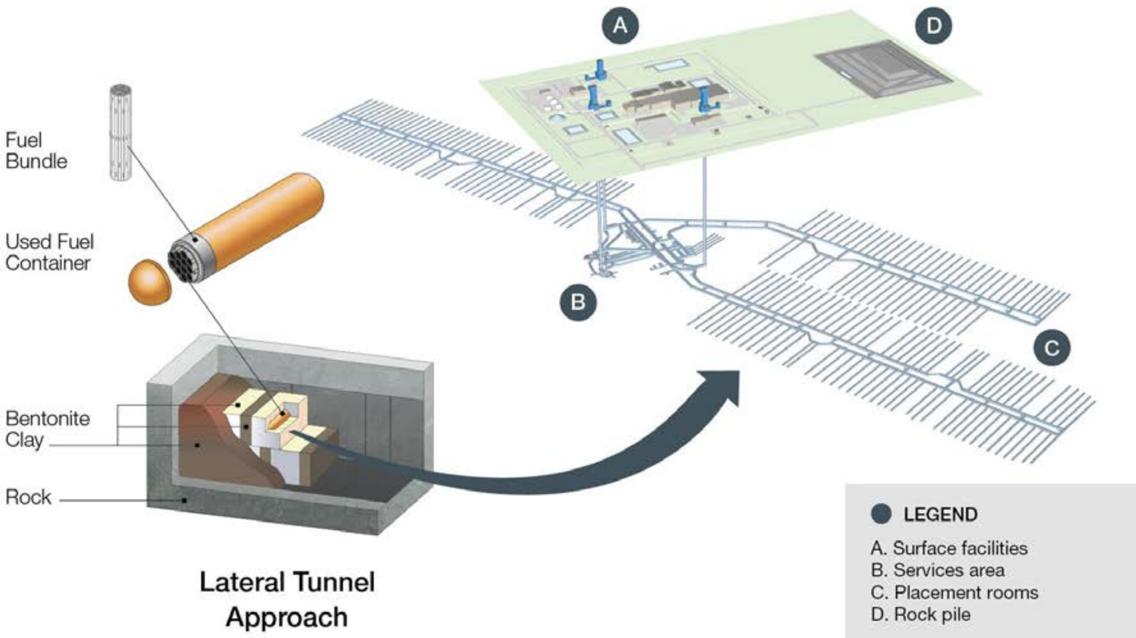


Figure 1-1: Illustration of a Deep Geological Repository Reference Design

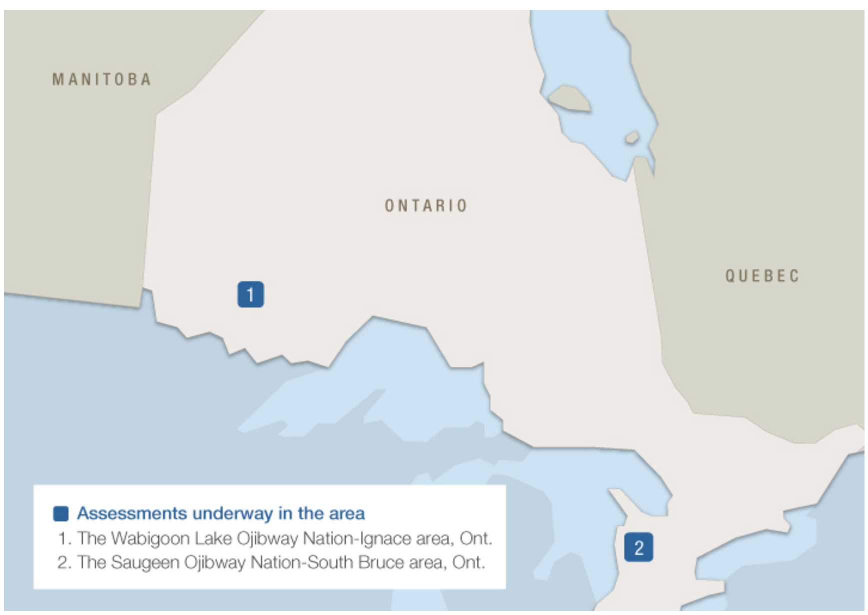


Figure 1-2: Interested Community Status as of 31 December 2023

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 2023 is summarized in this report. Prior years work is summarized in the 2022 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 2023 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 2023, the NWMO entered into an Agreement with the United States Department of Energy (USA/DOE) and continued its participation in the previous agreements with ANDRA (France), INER (Taiwan), KORAD (South Korea), Nagra (Switzerland), NDA (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 2023, 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 2023:

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

- Gas-Permeable Seal Test (GAST) at GTS.
- Enhanced Sealing Project (ESP) at Whiteshell Labs, Canada,
- MICA Michigan International Copper Analogue project, and
- International Bentonite Longevity project.

NWMO was involved with the following modelling or information exchange projects in 2023:
- DECOVALEX thermal-hydraulic-mechanical modelling,
- Post-closure criticality working group,
- CatchNET 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 2023, research and development progressed as planned in the Engineering Program:

1. The Proof Test Program to develop/demonstrate/ test the Mark II reference design Engineered Barrier System (EBS) fabrication and implementation technologies, as well to evaluate the EB materials ability to satisfy long term performance requirements in the DGR post closure environment, was completed.
2. Research and development continued on UFC copper coating processes as part of ongoing optimization of manufacturing methods.
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 Impact Assessment and Licensing activities.
5. Assessment of potential underground DGR layouts for the reference 5.5 million bundles storage capacity 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. Initial design concepts for the disposal of waste forms from new reactor technologies being deployed and/or considered in Canada and the impact on the EBS, UFPP and DGR design are being studied.

Summaries of these activities in 2023 are provided in the following sections.

3.1 DESIGN REQUIREMENTS

In 2023, no further design requirements work was initiated following the development of the three high-level design requirements (DR) documents completed in 2021. Details on the three documents can be found in the 2021 ATR (NWMO 2022). They provide the basis for the development of more detailed sub-tier design requirements and program requirements, and will be used to inform safety assessment, site evaluation, and project cost estimate updates.

3.2 USED FUEL TRANSPORTATION

3.2.1 Used Fuel Transportation Systems

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

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

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

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

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

NWMO's responsibility includes the development of a robust UFTS to ensure the safe and secure transport of Canada's used fuel. Projects in the areas of transportation collision data assessment and mitigation, confidence in transportation package performance, emergency management for transport of used fuel, as well as supporting the Whiteshell Fuel Transfer Project were areas of work in 2023.

3.2.2 Transportation Collision Data & Mitigation Assessment

In 2023, NWMO completed work on a study to analyze historical transportation collision data relevant to the types of conveyances considered in the above-noted UFTS concepts to better understand collisions, causal factors, and mitigation strategies. Federal and provincial level data was leveraged to assess both road and rail modes of transportation. The study culminated in the completion of two reports in the latter half of 2023 as follows:

Transportation Collision Data Analysis Report (AECOM 2023a): The study gathered, analyzed and assessed data on relevant modes and types of conveyances proposed to transport used fuel to the DGR. The study statistically assessed collision data to understand the types of collisions, severity, potential causal factors as well quantified transport collision probabilities.

Transportation Collision Mitigation Report (AECOM 2023b): Leveraging the above analysis, this report identifies potential processes, plans, preventative and mitigation measures that can be implemented in NWMO's future transportation campaign. Organizations with decades of experience with radioactive material shipments provided input on respective mitigation factors.

3.2.3 Confidence in Transportation Package Performance

In 2023, NWMO completed work on a study aimed at presenting, in a clear and concise manner, how the regulations and requirements pertaining to Type B transportation packages ensure that inherent safety is built into the package design (Calian 2023). Throughout the development of the Confidence in Transportation Package Performance report, prior studies from organizations specializing in used fuel transportation were leveraged to provide insights into the design of Type B packages, historical demonstration tests, and international experience in transporting used fuel as well as high level waste.

In addition, the study delved into real-world accident reconstructions carried out to assess the theoretical impacts of high-consequence accidents (such as tunnel fires and railway collisions) on transportation packages. The effects of notable Canadian accidents on NWMO's transportation packages were also qualitatively assessed within the study to provide further assurance that the transport of used fuel in certified Type B packages is safe.

3.2.4 Transportation Emergency Management Framework

In 2023, NWMO initiated a study to develop a foundation of knowledge upon which an emergency management framework for the transport of Canada's used nuclear fuel can be developed. This work intends to identify and highlight relevant regulatory and legislative requirements as well as identify the 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 used fuel. This work also leverages industry expertise regarding the processes involved during the identification and response to emergency situations during transport.

The scope of this study includes both road and rail modes of transportation, and considers federal, provincial, and local requirements for emergency response to incidents involving Class 7 (radioactive) dangerous goods, within which used fuel is classified. This study is ongoing and anticipated to be completed in 2024.

3.2.5 Whiteshell Fuel Transfer Project

NWMO is currently collaborating with Canadian Nuclear Laboratories (CNL) to support the Whiteshell Fuel Transfer Project aimed at consolidating used fuel storage. Used fuel currently stored at Whiteshell Laboratories in Pinawa, Manitoba, will be transported to the interim waste management facility in Chalk River, Ontario. To accomplish this, CNL has leased NWMO's Used Fuel Transportation Package (UFTP-1).

As part of this project, it is anticipated that CNL will use the UFTP to transport mixed fuel types (MFT) from the Dry Storage Concrete Canister Facility at Whiteshell Laboratories to CNL. Throughout 2023, NWMO collaborated with CNL to develop and submit a new application to the CNSC to certify the UFTP to carry MFT contents.

3.3 USED FUEL PACKAGING PLANT

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

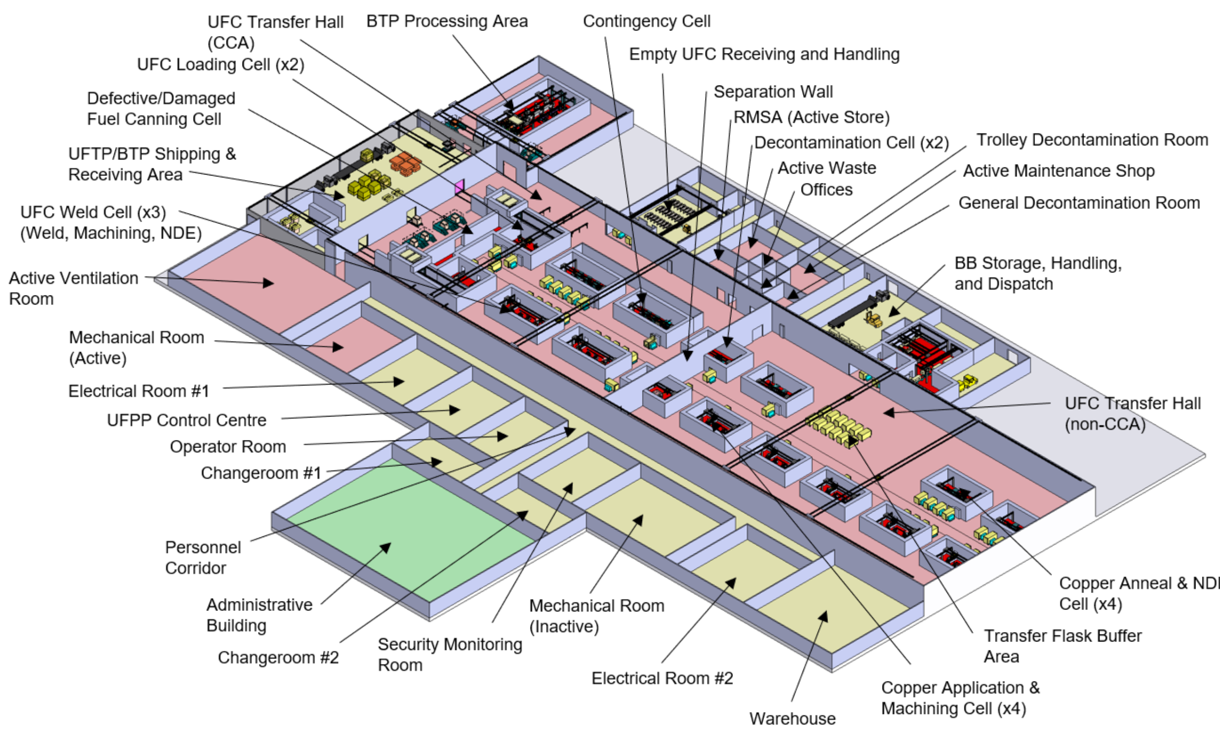


Figure 3-2: Concept Layout of the Used Fuel Packaging Plant (UFPP)*

*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).

While the development of the used fuel packaging processes and the UFC design have not been finalized, the maturing UFPP design will be developed alongside the maturing packaging technology and UFC design. Twelve key 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

The conceptual design for the UFPP was followed up in 2022 with a review of the packaging process development to date. In 2023, the consolidated reviews provided the inputs to the new work packages associated with the UFPP: (1) support of the Impact Assessment and Licence to Prepare Site Applications; and (2) advancing the design in selected areas for the UFPP.

3.3.1 Support of Impact Assessment and Licence to Prepare Site Activities

The preparation for, and launch of, the contract to support the Impact Assessment (IA) and Licence to Prepare Site (LTPS) began in 2022. The work under this contract builds upon the previous work on the reference conceptual design of Used Fuel Packaging Plant (UFPP) completed in 2021. The purpose of this work is to strategically advance the UFPP development in 2021 to align it with the needs of the IA and LTPS applications.

In 2023, work was completed for some of the UFPP systems to provide inputs to NWMO’s Effects Assessment work. For example, an initial estimate of the UFPP utilities (e.g., electricity, natural gas, water usage), waste generation, was completed based on the 2021 conceptual design. Due to the lack of maturity of the conceptual design, some assumptions had to be made and industry best practice and engineering judgement were applied.

The UFPP is a multifaceted facility, encompassing a range of multi-disciplinary Structures, Systems, and Components (SSCs) that has been organized into seven system categories. These systems, delineated based on their function and stage of progress align with the UFPP Conceptual Design, are as follows:

1. Fuel Packaging Systems (Estimate completed in 2023)
2. Facility Support Systems (Estimate completed in 2023)
3. Active Waste Management Systems (Estimate and design in progress)
4. Inactive Waste Management Systems (Estimate completed in 2023)
5. Ventilation System (Estimate and design in progress)
6. Operations, Control, Monitoring and Facility Services (Estimate completed in 2023)
7. UFPP Plant Infrastructure and Building Systems (Estimate and design in progress)

Each system category was assessed as a dedicated sub-work package. This approach provided the necessary design details to inform the key aspects of the IA & LTPS without duplicating efforts across packages. In 2023, four sub-work packages reached completion; the remaining work will be completed in early 2024.

3.3.1.1 Fuel Packaging Systems

The objective of this sub-work package is to calculate the inputs and outputs of the fuel packaging systems to support NWMO's IA and LTPS applications. This sub-work package encompasses the primary systems of the fuel handling process, from the receipt of the transportation packages, loading of fuel bundles into the UFCs and performing the UFC closure processes. Calculations within this sub work-package support the development of subsequent sub-work packages which include the Active Waste Management Systems and Operations, Control, Monitoring and Facility Services. Starting from clearly defined system requirements, an analytical process is conducted with an analysis of the equipment utilization to determine the material consumption rate and waste discharge.

3.3.1.2 Facility Support Systems

Beyond the primary systems, this category includes essential support systems, such as Empty Module /SFB (Spent Fuel Basket) Treatment System, transfer equipment, and Canning System. This sub-work package requires identifying the major process equipment before assessment, which were not as well defined previously comparing to the primary systems. Work started from outlining the equipment list and developing system process diagram. As the fuel packaging system was developed, an analysis was done to finalize equipment quantities and usages, leading to a comprehensive account of material consumption and waste discharge.

3.3.1.3 Active Waste Management Systems

The active waste management systems within the UFPP collect and process active solid and liquid waste that is generated within the UFPP. This sub-work package developed a conceptual design for the Liquid Radioactive Waste Management System (LRWMS) and the Solid Radioactive Waste Management System (SRWMS). Each system design was based on the waste inputs derived from the other sub-work packages.

The purpose of the LRWMS is to collect, treat and reduce the radioactivity levels of the liquid waste from the UFPP, allowing it to be discharged into the UFPP Inactive Waste Management System. The liquid waste is treated through the LRWMS which comprises of several components, including tanks, pumps, chemical injection nozzles, filtration vessels, and ion exchangers. Treated liquid waste is then sent to a verification tank where its activity and contaminant levels are measured to confirm all water that is discharged to the Inactive Waste Management System meets regulatory requirements.

The SRWMS will receive active solid waste from UFPP operations, maintenance and the LRWMS. The SRWMS will classify, sort, and process the solid radioactive waste. Once classified, waste will be packaged or sent to its appropriate processing area where it will be size reduced followed by compaction into a puck which is then containerized. Processing of solid waste will depend on type of waste, size, material, and classification.

3.3.1.4 Inactive Waste Management Systems

The UFPP will produce various waste during operation. Inactive Waste Management System's responsibility is the collection and disposal preparation of conventional (i.e., non-radioactive) waste. The technical memorandum from this sub-work package finalizes the SSCs design that facilitates waste collection and discharge from the UFPP. The systems are divided into three subsystems: 1) Conventional Liquid Waste Collection System, 2) Chemically Hazardous Liquid Waste Collection System, 3) Conventional Solid Waste Management System.

The completed summary sheets provide the calculations for projected Equipment List/ Component Bill of Materials (BOM), the associated usage, consumables, and outputs (i.e., waste generated from the systems). The design inputs and assumptions serve as the basis for the calculations. The summary sheets further describe the calculation methodology, engineering rationale and potential effects of changes to these calculations.

3.3.1.5 Ventilation Systems

The integrated Active Ventilation and HVAC (Heating, Ventilation, and Air Conditioning) systems are crucial components required for safe operation of the Used Fuel Packaging Plant. NWMO began conceptual design of these systems in 2023 with industrial partners as part of design development to support the preparation of IA and LTPS inputs.

The UFPP is divided into various areas, rooms, and hot cells, each with specific functions to support fuel packaging operations. The Active Ventilation system is designed to maintain containment of radioactive contamination in each area by ventilating air out through a specialized exhaust system at a constant rate while maintaining a low pressure in each area relative to the ambient external atmosphere. The number of air exchanges per hour and the depression reached in each room or area is proportional to the contamination risks in those areas. The outlet air of lower risk areas supplies the inlet air to higher risk areas. This design approach, called cascade ventilation, ensures that air always flows from the lower risk areas into the higher risk areas, and never in the opposite direction. The classification of each room and 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*.

Air entering the UFPP and subsequently exhausted from the controlled areas passes through several stages of filtration. Coarse filters are used at various stages to remove large particulate, which helps prevent clogging of the finer downstream filters. HEPA (High Efficiency Particulate Air) filters are used at the inlet of all hot cells, and at multiple points in the exhaust of all areas. Fan coil units each containing a pre-filter and HEPA are used to clean, condition, recirculate and exhaust air for each hot cell. In addition, HEGA (High Efficiency Gas Adsorber) filters containing activated carbon are used in the fan coil units at the cells that will handle open fuel assemblies. The exhaust from all areas will pass through multiple stages of filtration and monitoring before it is released from the building exhaust stack.

The HVAC system, partnered with the Active Ventilation system, provides heating and cooling for air in the UFPP to accommodate external weather conditions as well as the heat load from equipment and personnel. Roof-mounted make-up air units (MAUs) and air-handling units (AHUs) supply fresh air to the controlled spaces in the UFPP, which will be heated, cooled, and humidity-controlled to suit the seasonal changes expected at the site. Localized heaters and fan-coil units will be used in the occupied areas to maintain comfortable temperatures.

3.3.1.6 Operations, Control, Monitoring and Facility Services

Focusing on the UFPP's architectural systems, this sub-work package covers the UFPP's control systems and facility amenities. Deliverables include the design of exterior enclosures, such as walls and roofing, and the internal partitioning of rooms. A 'space program sheet' provides an index of space requirements for each UFPP room, with 'room-by-room sheets' detailing specific design needs. General arrangement layouts are depicted in the delivered drawing. The package also involves the electrical load list and water demand list by consolidating the data from other sub-work packages.

3.3.1.7 UFPP Plant Infrastructure and Building Systems

This sub-work package delivery will advance the conceptual design of the UFPP's plant infrastructure and building systems surrounding the workplaces. The summary report will specify the applicable codes and standards for the UFPP design. It will also outline the industry best practices for the design and construction of the building structure. The design requirements have been completed and the development of the design descriptions is underway.

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 protects 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.

3.3.2 UFC Closure Technology: UFPP Technical Feasibility and Risk Assessment Study

In 2022, NWMO initiated three independent third party reviews of the Mark II reference used fuel container (UFC) closure process operations (i.e., welding, copper cold spray). These reviews were conducted by three vendors with expertise in development of tooling and automation systems for production and manufacturing in high-radiation environments. A technical feasibility and risk assessment of the processes used to implement closure of the Mark II reference UFC was completed in 2023. Recommendations on potential UFC design changes to simplify closure in addition to potential tooling and automation solutions to mitigate UFPP operational risk are being reviewed as part of continued UFC and UFPP design evolution.

3.3.3 Collaboration with Posiva Solutions Oy Finland

Finland is the current leader in the implementation of used nuclear fuel packaging and underground disposal technologies (Mikhailova, 2019). The Onkalo disposal facility developed by Posiva will be 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 civil construction for the Onkalo encapsulation plant has been completed, and the equipment needed for the used fuel delivered.

NWMO has initiated a collaborative project with Posiva to engage their technical experts in used fuel packaging and handling to draw from this extensive experience. Through this collaboration, our Used Fuel Packaging Plant team, and other groups within NWMO, have been able to leverage the accumulated knowledge and lessons learned from Posiva's experts. This experience is being applied to our designs to improve the safety, efficiency, and reliability of used fuel packaging in Canada.

This work continued through 2023. A workshop on Posiva's fuel handling machine and process was conducted in the spring, and Posiva engaged their technical experts to review NWMO's reference codes, standards, and regulations for the UFPP as part of a holistic review of our facility design requirements.

3.4 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. This work is set to take place in 2024.

3.5 SITE AND REPOSITORY

3.5.1 Shafts, Headframes, and Hoisting Systems

3.5.1.1 Headframe Type and Hoist System Arrangement Trade-off Study

A trade-off study for a concrete headframe compared to a steel headframe solution in conjunction with tower mounted compared to ground mounted hoisting arrangements for the Main and Service Shafts of the NWMO APM DGR was conducted. The recommendation was to adopt a steel structure for the headframes of the Main and Service Shafts with ground mounted hoisting arrangements based on the results of this trade off study.

This recommendation is based on:

- Benefit of reduced headframe height associated with the change to ground mounted hoists.
- Ease of refurbishment and demolition – reconstruction of a steel headframe.
- There is improved opportunity to reconfigure / resize the facilities should the hoisting system requirements change over the complete facility life span, e.g., after the 70-year monitoring period, a different configuration may be preferred for the decommissioning stage lowering of backfill materials.
- Related to the replacement of the headframe or hoisting components it is possible to preassemble large components adjacent to the installed systems and then do a rapid exchange of the systems; thereby mitigating the down time. If this is timed for an idle stage of the DGR lifecycle, the importance of this is reduced.
- Ease of hoist and related system equipment maintenance for ground located hoist houses.
- Separation of the hoisting systems from the tower headframe to the ground located hoist rooms provide a lower fire risk consequence.

- Should incremental replacement of structural members be required, it is relatively easier with the steel headframe versus the concrete headframe to complete these remedial repairs.

3.5.1.2 Service Shaft Hoist Type Trade-off Study

A review of the Service Shaft hoisting plant was completed by Hatch to determine potential hoisting arrangements that would reduce the life cycle cost and provide improved value to the DGR. The recommendation was to adopt a system configuration for the Service Shaft considering three ground-mounted Blair hoists for the Excavated Rock Hoist, Service Hoist and Auxiliary Hoist. The Excavated Rock Hoist and Service Hoist are mechanically identical with the option to match electrical designs if the Service Hoist maximum rope speed is increased to 5 m/s, and the Auxiliary Hoist is mechanically and electrically identical to the Exhaust Ventilation Shaft Hoist.

The recommendation is based on:

- Benefit of reduced headframe height and shaft depth associated with the change to Blair hoists.
- Benefit of a reduced site footprint and cost due to the reduction in the quantity of hoist houses required.
- Benefit of reduced overall footprint of spares to be stored due to the common design, which maximizes common spares.
- Benefit of a shorter construction schedule associated with the reduced shaft depth, headframe height and shorter shaft changeover duration.

3.5.1.3 Headframe and Hoisting System Design

Calculations were completed to identify a preliminary duty cycle for the Main Shaft and Exhaust Ventilation Shaft Hoisting Systems.

These cycle calculations will drive the selection of equipment for the Main Shaft and Exhaust Ventilation Hoisting Systems, which will meet required Acceptance Criteria for the following main parameters:

- Duty cycle RMS power
- Head rope Safety Factor
- Drum to head rope diameter ratio
- Head rope tread pressure
- Static T1/T2 ratio
- Tail rope Safety Factor.

Additionally, several general arrangement drawings were drafted to conceptualize the headframe and hoist system configurations.

3.5.1.4 Shaft Sinking Temporary Ground Support Design

Rock support requirements for the shaft development at the Revell and South Bruce Sites were estimated. These estimates will be used in the development of excavation cycle times (installation time) for the shafts and will inform the material take-offs, cost estimates, and schedule.

Support requirements for the shafts are driven by worker safety. For the Revell Site, the recommended minimum support is a mechanically anchored bolt or split set on a bolt pattern of 2.0 m × 2.0 m with the purpose of securing mesh (e.g., chain link or 102 mm × 102 mm #6 gauge welded wire mesh) for the protection of workers. The recommended length of the bolts to secure the mesh is 1.2 m. Spot bolting shall be designed as required to address local conditions.

For the South Bruce Site, support requirements for the shafts vary from formation to formation. Based on the zones of overstress, primary support was estimated for three ground conditions; rock formations with no overstressed zone, rock formations with overstressed zone, and rock formations with overstressed zone and/or potential for slaking to occur.

3.5.2 Underground Repository Design

The design layout and 3D models of the repository for both the Revell and South Bruce Sites were advanced. This included the design of the placement rooms and all ancillary infrastructure facilities required to carry out the operations. Additional rooms will be developed specifically to address the geoscientific plan, while some ancillary facilities will also be temporarily used for geoscientific purposes early in the development.

The high-level scope includes excavation space for:

- Services area and Amenities, including:
    - Excavated rock handling system
    - Service water, dewatering, and water recycling systems
    - Mobile and fixed equipment maintenance facilities
    - Road ballast crushing system
    - Non-nuclear material handling and temporary storage facilities
    - Electrical and communications systems and equipment
    - Mobile equipment parking and battery charging facilities
    - Refuge stations, lunchrooms, lavatories, offices
    - Underground demonstration facility (UDF)

- Placement arms with panels of placement rooms:
    - Placement rooms for the used fuel container (UFC) placement
    - Ventilation systems for the placement arm and placement rooms
    - Routing to separate the excavation of one panel of rooms while another is placing loaded buffer boxes (LBBs).

3.5.3 Underground Mobile & Portable Equipment Fleet Estimation

A preliminary list of underground mobile and portable equipment required for the construction and operations phases of the APM DGR facility was developed to a pre-feasibility study level.

Equipment such as Load Haul Dumps (LHD’s) and trucks typically use a diesel engine as their sole power source, whereas equipment such as jumbos are typically connected to mine power when drilling and rely on a diesel engine when tramming. In recent years manufacturers have started developing battery electric vehicles (BEV)’s that can operate without a diesel engine.

Based on the mining industry transition taking place, it is now acknowledged that all underground mobile equipment will be battery powered by the time the DGR is constructed. Where a BEV version of a piece of mobile equipment does not currently exist, a diesel equivalent will be listed with the assumption that a BEV equivalent will be available in the near future.

3.5.4 Testing of Rock Core Samples for Potential Re-use of Excavated Rock

Testing was carried on rock core samples from the Revell and South Bruce Sites. The objective of this work was to test rock core collected during investigations at the Revell and South Bruce Sites for the purposes of assessing the rock’s potential future use as aggregate for construction purposes.

The composite sample tested from the South Bruce site indicates that the Cobourg Formation could potentially be used as Granular A and B construction materials and is also suitable for general use in construction. The South Bruce material can also potentially meet the Concrete Stone specification OPSS 1002 with appropriate processing. Further testing of the South Bruce material would be needed to assess its suitability for road use. The South Bruce material may also meet Class 1 through 6 stone requirements as per OPSS 1006 pertaining to the use of aggregates for surface treatments with appropriate processing.

The composite sample tested from the Revell Site indicates that it can be used as Granular A and B construction materials and is also suitable for general use in construction. The Revell material is also considered suitable for Concrete Stone and meets specification OPSS 1002 and is considered suitable for road use as Class 1 through 6 stone as per OPSS 1006 pertaining to the use of aggregates for surface treatments.

3.5.5 Excavated Rock Management Area

The design of the Excavated Rock Management Area (ERMA) was updated to reflect site conditions at Revell and South Bruce Sites. A siting options study was completed for South Bruce Site to determine a preliminary location for the ERMA that minimizes effects on potential wildlife habitat. Preliminary slope stability calculations were carried out to assess constructability of the design. The ERMA design considered mitigation of visual impact by building berms for screening the view from adjacent roadways and included preliminary designs for stormwater collection ditches and the dedicated stormwater management pond.

3.5.6 Repository Operations Plan

A major input to the overarching Operations Plan is an assessment of the ability of the current design to support the operational throughput of the DGR to receive, process and emplace used nuclear fuel within the repository. A Functional Description was prepared to define the inputs and operating logic which form the model basis using dynamic simulation. Dynamic simulation is the preferred methodology for evaluating complex systems because, unlike spreadsheet models or linear programs, it captures the dynamic effects of system interactions, process variation, random failures, competition for resources, logistical constraints, process constraints, and other phenomena observed in real systems and quantifies the cumulative capacity losses associated with them. This functional description will serve to inform the simulation and eventually the Operations Plan Report.

3.5.7 Surface Water Management Program for DGR Sites

The NWMO has begun to advance the development of the water management programs for the unique site-specific geosphere and surface conditions. based upon an established set of guidelines (Mahoney et al. 2023). An important focus is to also minimize its environmental footprint. The program aims to ensure water taken from the environment is minimized, water on-site is recycled to the greatest extent possible, and water discharged to the environment meets an established criteria.

The following have been considered in the design of the service water and stormwater management systems: post-development catchment areas and associated peak flows based on meteorologic data; the site framework layout; finished grading design; and preliminary road design. Hydraulic calculations for the sizing of drainage infrastructure (i.e., stormwater management ponds, ditches, culverts, storm sewers, catch basins) are based on a 1-in-500-year storm event for the protected area and balance of site. In addition to the stormwater management ponds for the protected area, the balance of site, and the excavated rock management area; there are the DGR water settling pond and the service water settling pond, along with engineered wetlands to hold treated water prior to release.

3.5.8 Remediation Strategies for Placement in Inferred Fracture Zones

To facilitate placement operations in less-than-ideal geosphere conditions, remedial strategies have been developed to accommodate a range of possible problematic environments (Solis et al. 2023). Of concern with respect to rock conditions and their impact on UFC placement are the local fracture networks that can potentially provide water to the open excavations. Depending on the water inflow, in combination with other factors, these remedial efforts could include; abandonment of a portion of, or a full room; grouting of the water-supplying feature(s); installation of a bentonite/concrete intermediate seal; or the use of simple floor drainage or localized water intercepting installations. Solutions could also include the use of modified Loaded Buffer Boxes, Spacer Blocks and Gap Fill Material placement techniques.

One straightforward strategy would be to seal the fracture zone with grout to reduce water inflow, and quickly place blank buffer boxes and bentonite gap fill in an exclusion area adjacent to the fracture zone as illustrated in Figure 3-3. This strategy should allow placement of the loaded buffer boxes to proceed within the placement room.

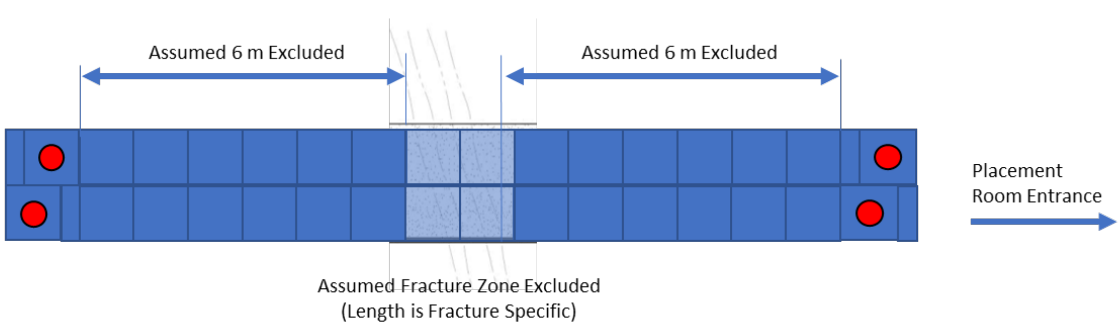


Figure 3-3: Blank Buffer Block Configuration for IFZ Less than 1,000 m

3.5.9 Aboveground Amenities Technical Design Update

The Aboveground Amenities are part of the DGR Surface Facilities, which includes the buildings, general services, and infrastructure required to support the DGR operations aboveground and the equipment associated with ventilation air, compressed air, and electrical services to the underground operations. The buildings and structures of Aboveground Amenities include buildings that are generally considered “conventional” to the nuclear and mining industries (e.g., offices, garage, storage, laboratories, etc.).

The purpose of this technical design update is to document the design of the Aboveground Amenities within the architectural scope that includes the buildings listed in Table 3-1. The building designs were advanced to support an AACE Class 4 cost estimate. The scope of this memo covers the design and developments of the facilities and how they will function.

Table 3-1: List of Aboveground Amenities

Facility Name
Administration Building including Emergency Response Centre
Repair Garage and Warehouse
Fuel Storage Tanks and Dispensing Station
Central Mechanical Services Building
Exterior Fence Security Building
Guard House
Storage Yard
Used Fuel Transportation Package Truck Wash
Auxiliary Building
Quality Control Offices and Laboratory
Security Monitoring Building A
Security Monitoring Building B
Emergency Response Building

Further study is required to develop the design of the building systems and services, including architectural details, structural, mechanical, HVAC, communication systems, electrical systems, and services, as well as equipment requirements such as overhead crane capacities.

3.5.10 Radiation Protection and Monitoring

The design of site facilities must include the infrastructure to support a radiation protection program. Central to the infrastructure is the need to identify a radiological zoning framework. APM facilities have used a preliminary zoning framework based on external dose constraints and the potential for contamination. These preliminary zoning constraints were reviewed and updated based on experience applying these zones to facility designs and best practices. Future work will focus on further developing the infrastructure required to support a radiation protection program, including identification of facility radiological zones, identification of radiological monitoring requirements, identification of tools and equipment, and ensuring the facility can support other interface with the radiation protection (e.g., training, signage, access control, personal protection equipment).

3.5.11 Compressed Air System

The Compressed Air System was advanced based on new design inputs from interfacing systems for both sites. The overall site framework layout, underground mobile equipment, and new design developments from the key operational facilities (UFPP and underground services) served as the key design inputs for this system. Based on the existing inputs, the design was advanced to a sufficient level of detail to provide input for the AACE Class 4 Cost Estimate. The Compressed Air System includes the following subsystems:

a) A Breathing Air System that provides purified Breathing Air to the refuge stations underground.

b) A Service Air System that provides Service Air to a range of facilities at the surface and underground. This includes Service Air to feed into the internal UFPP Breathing Air System.

The Breathing Air System and Service Air System comprise three shared compressors, a shared storage system, and a shared distribution system. The shared distribution system will connect to Breathing Air purifiers to purify air to Breathing Air quality.

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 4.4, respectively.

4.1 USED FUEL CONTAINER (UFC) REFERENCE DESIGN

In 2023, the NWMO completed the execution of the Proof Test Program to validate the Mark II reference (conceptual) design of the Used Fuel Container (Figure 4-1, Figure 4-2, Figure 4-3). This includes completing the UFC serial production campaign for the demonstration of reference manufacturing and inspections processes, validation testing to confirm the structural performance of the design and completion of design analysis activities. R&D activities continued on select UFC manufacturing operations as part of ongoing continuous improvement on the reference design.

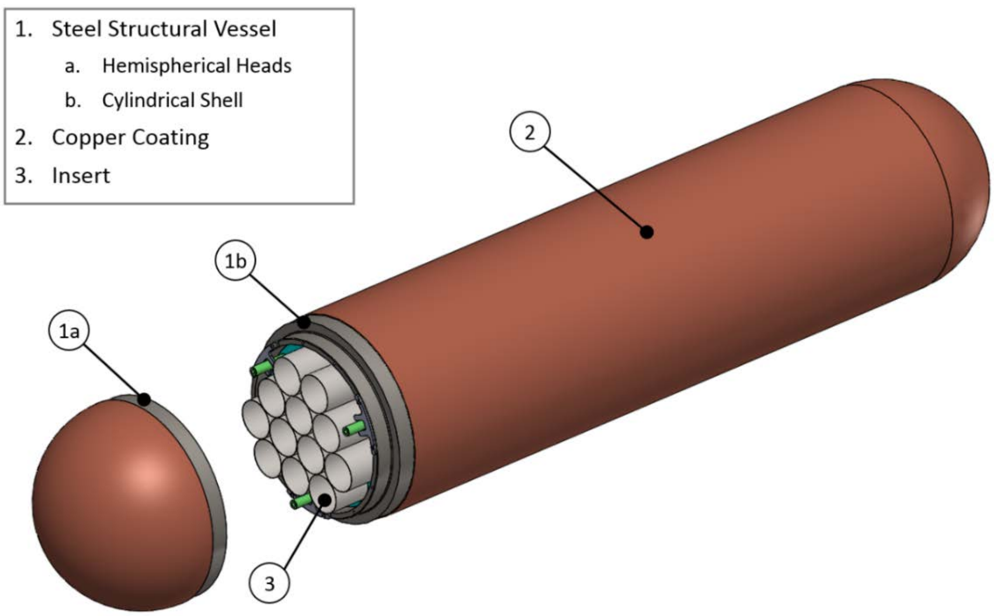


Figure 4-1: Illustration of the Mark II Used Fuel Container Reference Design

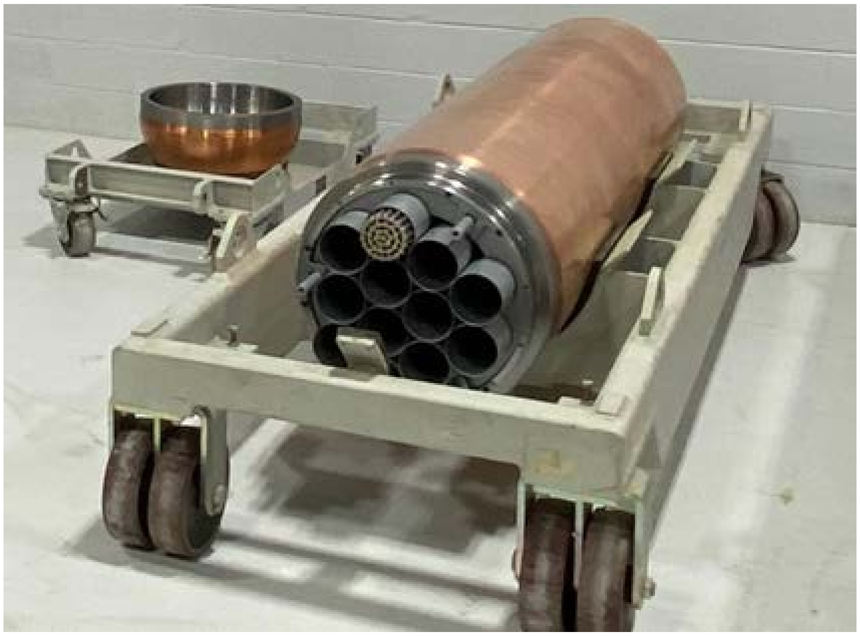


Figure 4-2: Mark II Used Fuel Container Reference Design Components (hemi-head, lower assembly and internal insert)

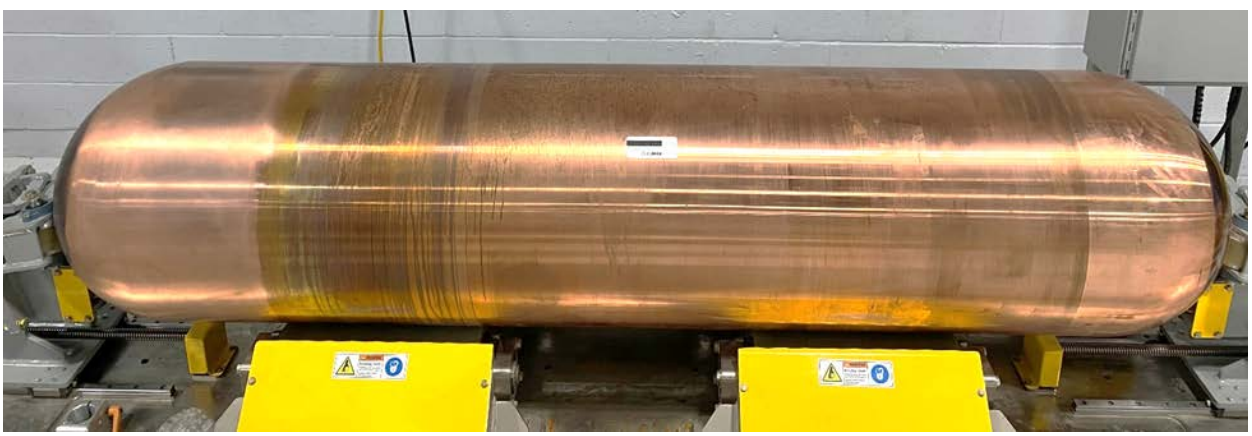


Figure 4-3: Assembled Mark II Used Fuel Container Reference Design

4.1.1 UFC Design Evaluation

In 2023, all the design evaluation tasks for the reference Mark II UFC were completed. The scope included more than twenty calculation and technical memorandum documents covering design load compilation, stress analyses, dynamic simulations and sensitivity studies. The evaluations were based on two generic sites (i.e., one with the sedimentary rock formation and the other with the crystalline rock formation) and the conceptual designs of the repository and its surface facilities. The UFC was evaluated for postulated service conditions and bounding conditions based on the best available data using design criteria commensurate with the risks and safety objectives associated with the proposed pre-closure operations and post-closure conditions. For the pre-closure period, the design criteria from ASME BPVC 2023 Section III, Division 3, Subsection WC were adopted with modification to accommodate the unique features needed for the disposal application. For post-closure, the UFC was evaluated for two distinct periods, i.e. within and beyond 10,000 years after repository closure, using criteria developed based on the containment requirements from IAEA SSR-5. The evaluation demonstrated the UFC's ability to withstand all normal and off-normal operational loads and major repository loads, including the bounding external pressure induced by a 3000-meter-thick glacier during ten future glaciation cycles. The UFC was predicted to well maintain its structural strength and stability over ten cycles of the extreme load, which was further demonstrated by full-scale external pressure tests on the Serial Production prototypes. The tests also revealed that there was sufficient design margin against the major repository load. The UFC's performance under accident operational conditions were also investigated, including the fire and drop conditions. The UFC's structural strength to withstand a conservative hypothetical fire scenario was evaluated using numerical simulations. For drop accidents, drop height thresholds were established based on the UFC response under various scenarios to inform the UFPP design and pre-closure safety assessment. The UFC design evaluation results have been summarized in a conceptual design report to be issued in early 2024.

4.1.2 UFC Design Verification

In 2023, a fourth external pressure test for the design verification of the Mark II reference UFC was completed by C-FER Technologies (Edmonton, AB). This is the last design verification test in the Mark II external pressure testing program. The test was conducted on a copper coated Serial Production UFC prototype, representing the state of art in container design and manufacturing. This round of the pressure test was built upon the success of the previous pressure test on a steel container reported in 2022. The purpose of the experiment is to further confirm the structural performance of the UFC with an additional scope to verify the performance of the copper coating under design basis loads (i.e., 10 cycles of glacial pressure) and beyond design basis conditions (i.e., collapse).

Same as the previous test, the cyclic glacial pressure test was conducted using C-FER's Deepwater Experimental Chamber (DEC), as shown in Figure 4-4. The buckling and post-buckling collapse tests were conducted using a secondary vessel inserted inside the DEC for additional pressure capacity. Figure 4-5 shows the UFC before and after applying the 10 cycles of glacial design pressure (i.e., 45 MPa). The container geometry remained unchanged, which was confirmed by geometric scanning data. In the buckling test, the UFC started to collapse at a pressure of about 67 MPa. This critical buckling load is higher than the previous steel container by 6%, roughly denoting the contribution of the copper coating to the overall buckling strength. The test showed that the safety factor against buckling is about 1.5. Figure 4-6 shows the container after the buckling test. In the last stage of the pressure test, the UFC was fully collapsed, as shown in Figure 4-7. Helium leak testing was conducted after the buckling test and the full collapse test, respectively. The UFC remained leak tight after both stages. A visual inspection was conducted to examine the copper surface after the full collapse test. No signs of cracking were observed.

The external pressure tests conducted to date confirmed that the UFC met the design basis conditions (e.g., 10 cycles of 45 MPa glacial pressure) without any significant permanent deformation. The safety factor against buckling or collapse is more than 1.2 in general and reached 1.5 on the final prototype. Additional safety margin was demonstrated as the fact that the UFC materials, including the base metals, weld and copper coating, were sufficiently ductile to maintain leak tightness even under severe plastic deformation in the beyond design basis condition (i.e., post-buckling collapse loading). The integrity of the UFC design, the effectiveness of the design method and the quality of the fabrication processes were well demonstrated by the external pressure testing program.

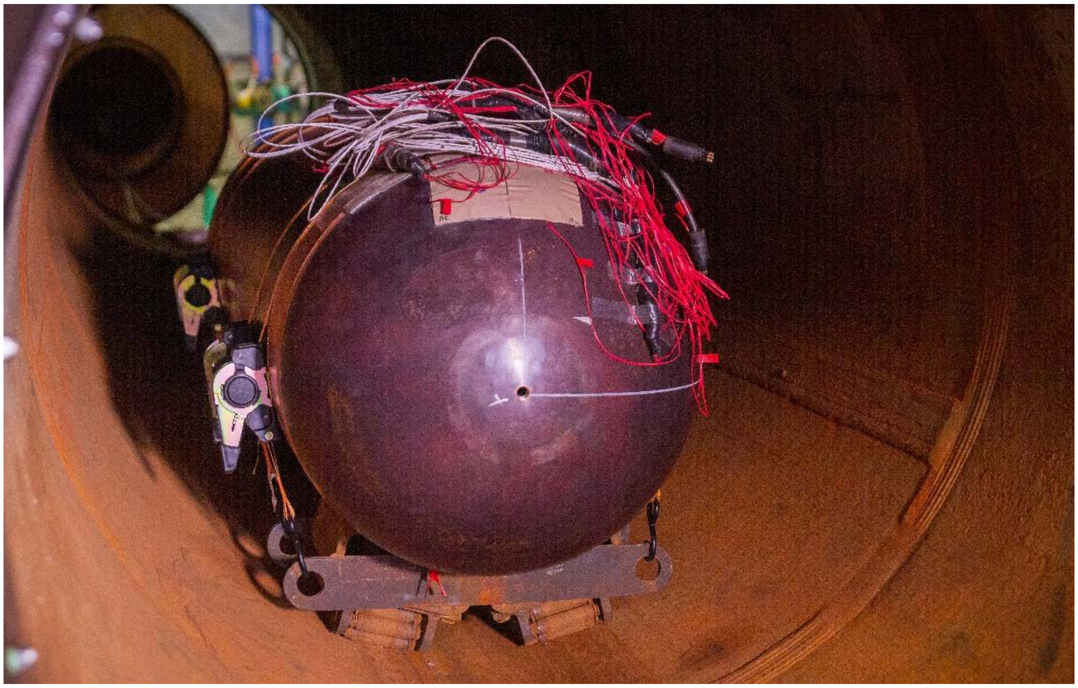


Figure 4-4: Serial Production copper coated Mark II UFC inside the Deepwater Experimental Chamber at C-FER Technologies

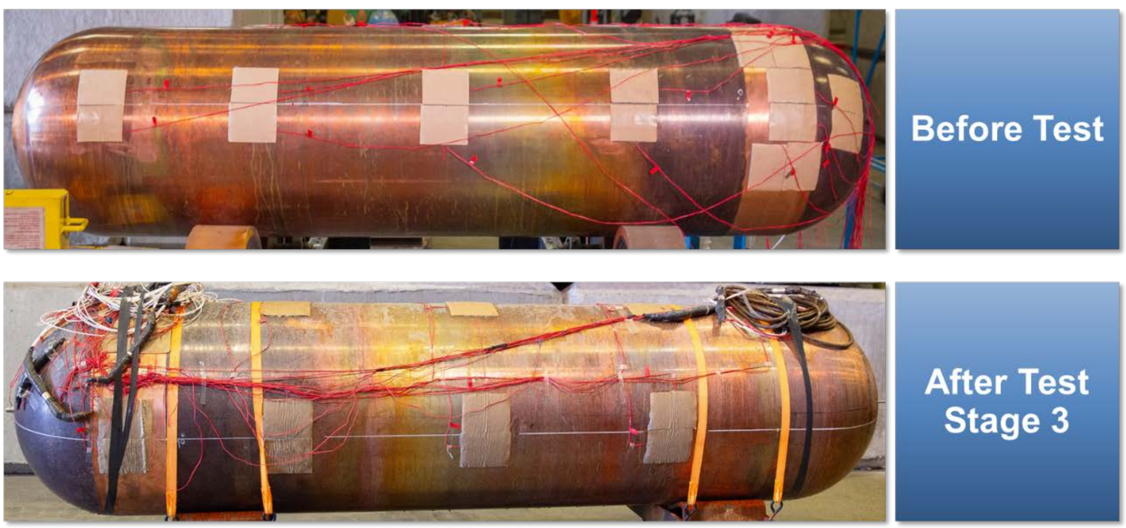


Figure 4-5: Comparison of copper coated Mark II UFC before and after applying 10 cycles of glacial design pressure

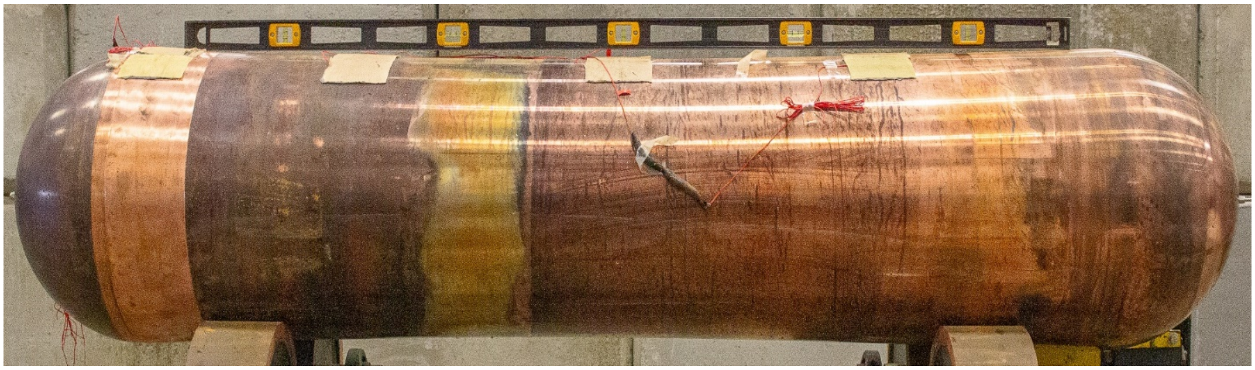


Figure 4-6: Copper coated Mark II UFC after the buckling test with a buckling pressure of 67 MPa

Figure 4-7: Copper coated Mark II UFC after post-buckling collapse loading (beyond design basis condition); leak tightness verified after severe plastic deformation.

4.1.3 UFC Serial Production

The work under the Serial Production Program has been completed. The main objective of Serial Production Program was to demonstrate in sufficient quantity, the manufacture of the Mark II UFC conceptual design incorporating selected materials, fabrication and inspection technologies, procedures and preliminary acceptance criteria. While the plan allowed for up to twenty UFC prototypes to be fabricated, twelve UFC's were fully completed (ten copper coated and two steel units). An additional five copper coated UFCs were progressed to an advanced state of completion. The quantity of units produced was sufficient to draw conclusions on the confidence of the design and manufacturing technologies. The state of the manufacturing and inspection processes for application to the UFC design, considerations on high-volume production and technology gaps have been documented. Critical characteristics important for success in each manufacturing process have been identified. A technical report documenting the Mark II UFC manufacturing development program is under preparation.

The UFC Serial Production Program demonstrated the following:

1. A supply chain for the procurement of the UFC structural steel components (hemi-spherical heads, shells) meeting NWMO technical specifications has been established.
2. Two different manufacturing sequences have been established for the assembly of the UFC based on electrodeposition copper coating supply chain options.

3. Machining methods / tooling / procedures for intermediate and final machining of UFC steel and copper coated components have been demonstrated.
4. Welding technology for application of the structural vessel partial penetration closure weld via Laser Pre-Heat Gas Metal Arc Welding (LP-GMAW) have been demonstrated.
5. Electrodeposition technology for the application of copper coatings on UFC Shell, lower assembly (LA) and HH components has been demonstrated via the acid copper process utilizing a NWMO developed pilot line (Integran Technologies Inc. (Integran), Mississauga, Ontario, Canada) and a commercial supplier (BEP Surface Technologies Ltd. (BEP), Manchester, United Kingdom).
6. Cold spray technology for application of copper coating to the closure weld zone has been demonstrated.
7. Non-destructive inspection methods / procedures and equipment for the examination of UFC structural vessel welds and copper coating have been demonstrated.
8. A prototype design of the internal insert was designed and manufactured.

The current state of reference technologies and materials employed in Serial Production were validated by full scale external pressure testing of steel and copper coated UFC's; these results are discussed in Section 4.1.2.

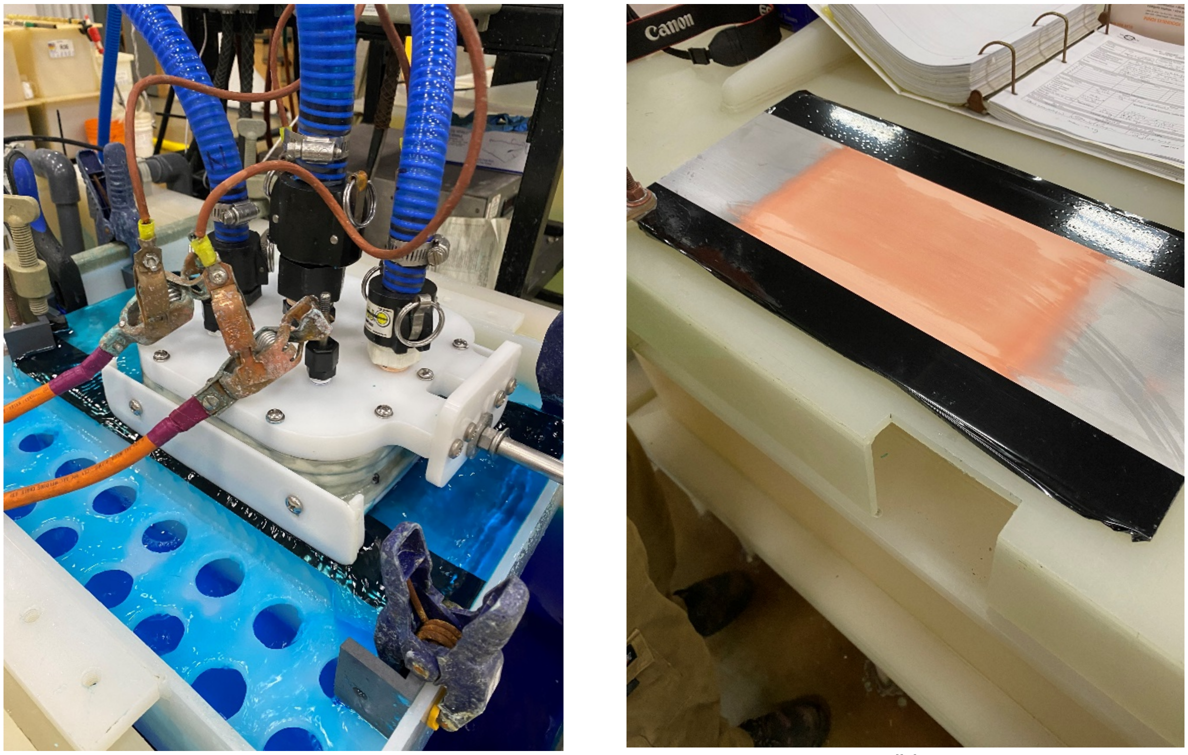
4.1.4 UFC Copper Coating Development

Continued development in copper coating technology was progressed in 2023. These advancements are discussed in the following sections.

4.1.4.1 Electrodeposition – Exploring a Copper Brush Plating Configuration

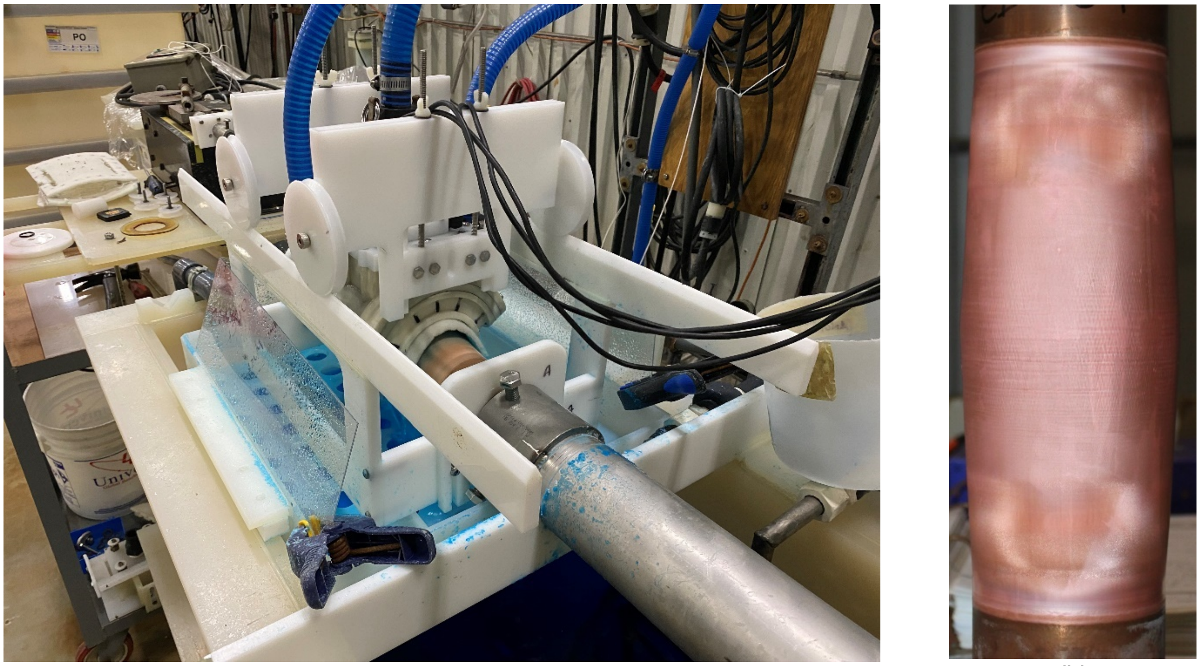
Building on the positive results from the acid copper development and implementation in serial production at Integran Technologies from the previous years, a new project was initiated to increase plating rate and thereby improve cost effectiveness. The objective of the new work was to adapt the acid copper process previously developed to a “brush” plating configuration while meeting the NWMO's material performance requirements. A final proof of concept would be performed on the outer diameter of a small-scale pipe geometry.

Integran designed, constructed, and optimized a plating system that was used to selectively brush electrodeposit copper. This development started by electroforming copper onto flat panel (Figure 4-8) followed by the small-scale pipe geometry (Figure 4-9). In both cases a specific plating apparatus for selective brush plating (named the flow-through anode applicator) was designed and optimized by performing plating trials. The process was demonstrated with samples produced for testing to determine material performance. In the case of the flat panel, free-standing copper deposits were produced to approximately 0.7-1.4 mm in thickness whereas the small-scale pipe geometry reached a thickness of 5.5-6.5 mm.



(a) (b)

Figure 4-8: Flat panel brush plating: (a) flow-through anode applicator oscillating unidirectionally over a stationary cathode and (b) copper deposit on cathode surface.



(a) (b)

Figure 4-9: Small-scale pipe geometry brush plating: (a) flow-through anode applicator oscillating unidirectionally over a rotating cathode and (b) copper deposit on pipe geometry.

The project was successful at achieving a plating rate that was greater than 3 times the conventional method's capability. The copper material extracted from the small-scale pipe geometry met microstructural and mechanical performance requirements (i.e., hardness and bend ductility). The purity of the copper was also deemed acceptable at > 99.9 %. Specific impurities were at or slightly above limits, therefore a recommendation for further optimization was put forth by Integran.

4.1.4.2 Electrodeposition - Alternative Copper Plating Method for Mark II Lower Assembly and Hemi-head Production

Following the success to assess an alternate commercial electrodeposition method for the supply of copper coated UFC shells in 2021, BEP Surface Technologies performed a demonstration trial to copper coat a lower assembly (Figure 4-10) and upper hemi-head (Figure 4-11). This included the design and build of a fixture specific for these components. Both components were coated without any visual defects and then shipped back to Canada for further machining and non-destructive examination that will be completed in 2024.

Figure 4-10: As-deposited condition of copper coated Mark II UFC lower assembly component at BEP.

Figure 4-11: As-deposited condition of copper coated Mark II UFC upper hemi-head component at BEP.

4.1.4.3 Cold Spray Process Improvements

At the conclusion of the UFC serial production program, several process improvements owed to scaling of the cold spray coating process were identified. One critical step in the process which was addressed was the bond layer application. To promote process robustness, stringent control over stand-off distance and laser alignment is required to achieve an adherent bond layer without showing indications of dis-bonding after non-destructive examination via ultrasonic testing. Part alignment in the UFC rotational equipment and on-line feedback control to maintain stand-off distance was therefore deemed necessary.

In partnership, the National Research Center (NRC) (Boucherville, Quebec) and Polycontrols (Brossard, Quebec) within the PolyCSAM Industrialization Centre (located at the NRC facilities in Boucherville, Quebec) pursued the implementation of a laser guided stand-off distance control using robotics. This first involved programming the robot to respond to distance measurements and adjusting accordingly to variations in real-time (Figure 4-12). Following this, the developed process was trialed on an off-centered pipe segment then eventually demonstrated on a UFC lower assembly with a mock-up closure weld zone (Figure 4-13). As a measure of effectiveness, the closure weld zone on the lower assembly was subjected to non-destructive examination primarily to assess bond integrity using ultrasound. In this case, a marked improvement was seen whereby the resulting coating showed very minimal indications over the steel portion of the closure weld zone.

Figure 4-12: Programming of spray gun equipped with laser guidance (affixed to nozzle) while traversing upward on a variable diameter rod.

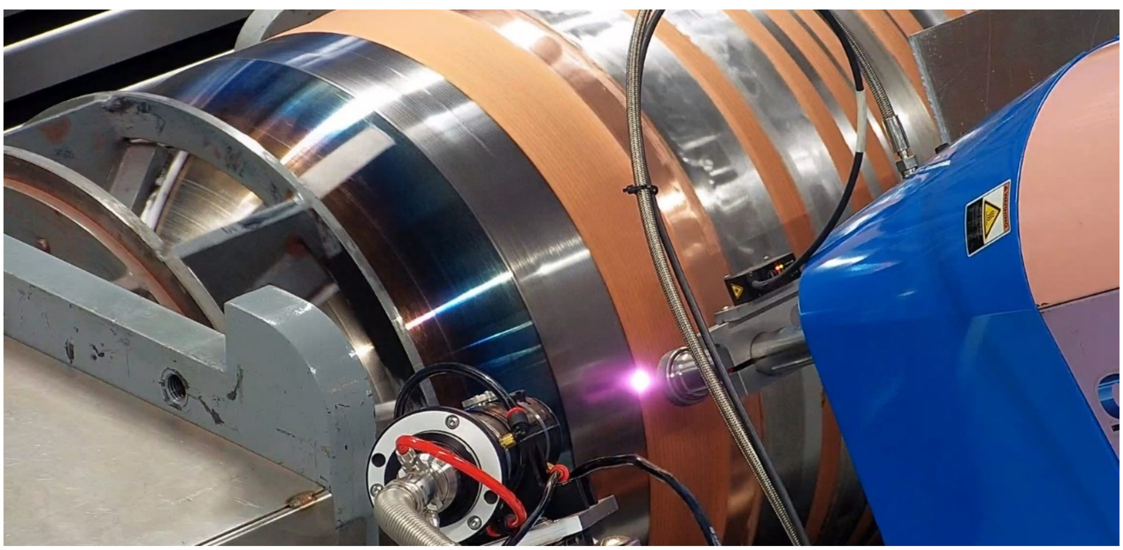


Figure 4-13: Implementation of the laser guided stand-off distance control to a mock-up closure weld zone on a lower assembly.

4.2 EBS INNOVATION INITIATIVE

The potential introduction of new high-level nuclear waste forms like Small Modular Reactor (SMR) fuel to Canada's waste inventory has initiated the NWMO to begin working on conceptual-level studies to examine Engineered Barrier System (EBS) options. These will potentially include a new UFC concept and a review of potential changes to the engineered barrier system, the processes in the Used Fuel Packaging Plant, as well as emplacement of the UFCs in the repository. These studies will be progressed in 2024.

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. However, this oxygen will be consumed by mineral reactions, aerobic microbial metabolism and corrosion leading to a highly reducing environment for the majority of the DGR's lifetime. The absence of oxygen creates an environment in which copper, the corrosion barrier of the UFC, is thermodynamically immune to corrosion provided that the pH of the groundwater does not reach extreme low values, which is not anticipated. However, while 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 virtually eliminates this possibility, the effects of bisulfide on the integrity of the UFC and the quantification of any such corrosion is important to understand. Additionally, since there remain two potential host sites for the Canadian DGR, the specific groundwater chemistry of each site must be investigated in conjunction with the effect of bisulfide. With respect to corrosion, the dominant species in each case is chloride which is being studied at various concentrations in conjunction with bisulfide.

Work being conducted by NWMO at CanmetMATERIALS (Hamilton, Canada) in collaboration with the University of Toronto and Queens University continues to investigate the individual and the combined effects of bisulfide and chloride along with pH effects in an anoxic environment. In the absence of oxygen, any potential corrosion reactions will produce hydrogen as a product which can be captured in the headspace of the specialized corrosion cells used in this research, shown in Figure 4-14(a). A detailed description of this apparatus was published by Senior et al. 2020. This hydrogen is then passed through a highly sensitive solid state ceramic sensor which can quantify the hydrogen. Using the known stoichiometry of the potential corrosion reactions, copper corrosion rates are then calculated. Notably, the release of trapped hydrogen from within the copper, or the production of hydrogen from other corrosion reactions within the cell (i.e., through the interaction of steels and water) will be assumed to be copper corrosion using this calculation method, and this will overestimate copper corrosion (Senior et al. 2019). The design of the corrosion cells allows for the online spiking of experiments with gaseous hydrogen sulfide, which dissolves in solution as bisulfide, thereby simulating the potential effects of microbiologically-induced corrosion at 75°C. Sample data showing the cumulative hydrogen measured and the calculated corrosion rates over a period of six years are shown in Figure 4-15 for the repository copper materials. With a representative immersion environment, the hydrogen generation and therefore the calculated corrosion rates consistently decline with time.

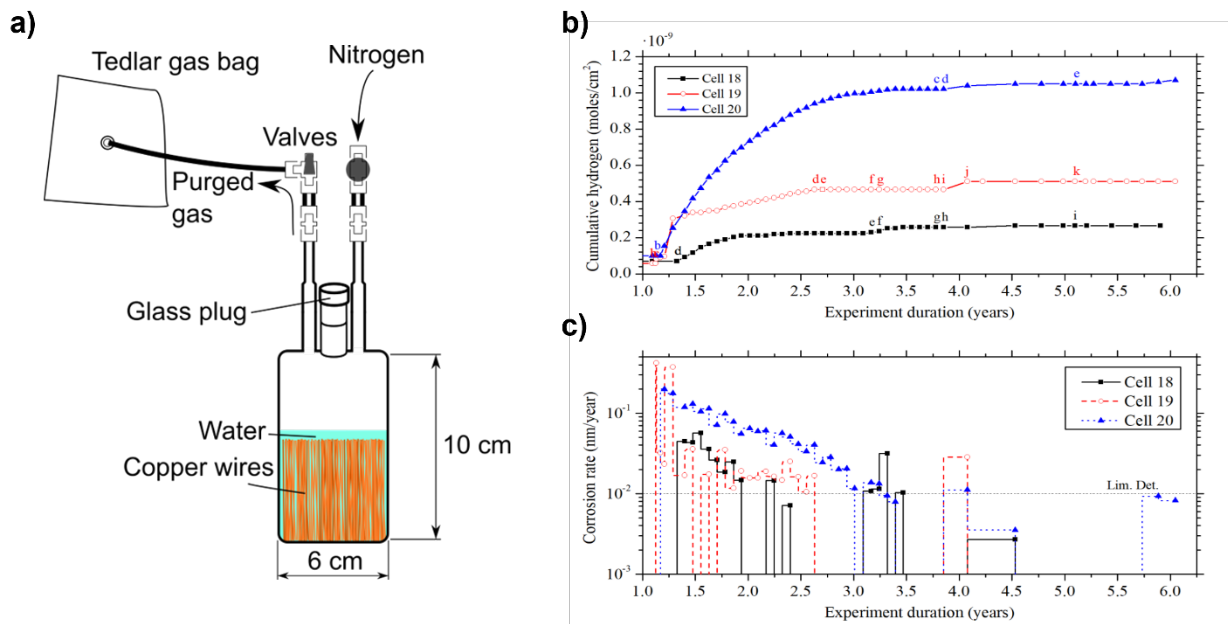


Figure 4-14: (a) Schematic of Test Cells for Anoxic Copper Corrosion Investigations at CanmetMATERIALS; (b) Cumulative measured Hydrogen and Calculated Copper Corrosion Rates for Three Cells Containing Cold Spray, Electrodeposited, and Junction Material, all in Simulated Canadian Groundwater Versus Time.

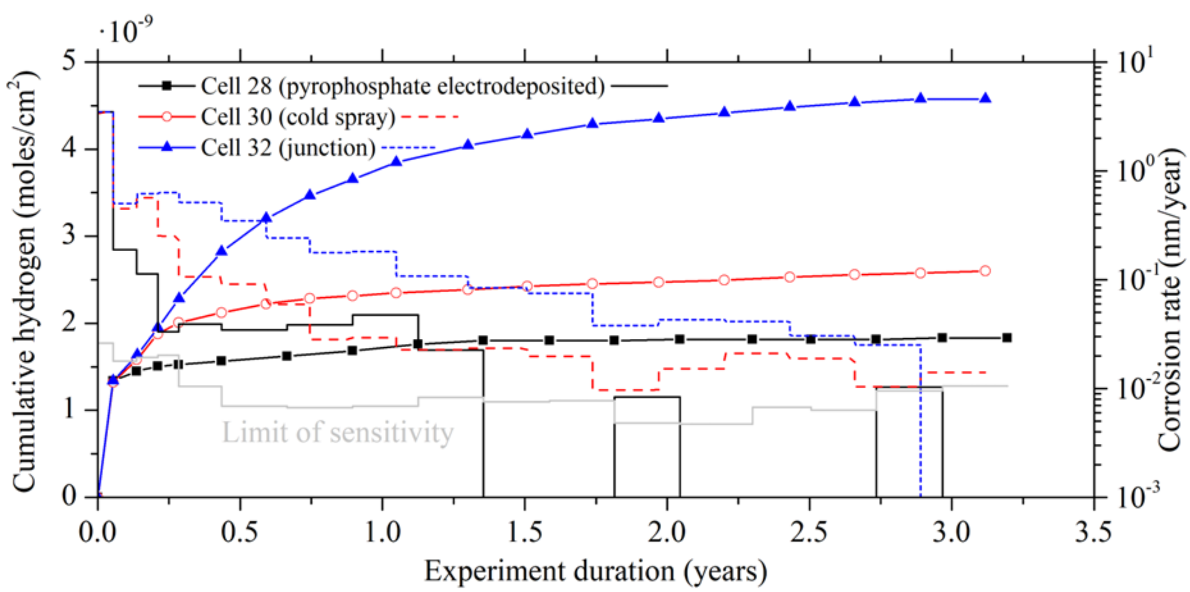


Figure 4-15: Long term corrosion experiments for repository copper materials in waters found in sedimentary host rocks (solid lines for cumulative hydrogen and dashed lines for the corrosion rate): Cell 28 – bulk copper coating on UFC components using electrodeposition, Cell 30 – cold sprayed copper coating at closure weld zone, and Cell 32 – junction where electrodeposited and cold sprayed copper meet to complete the coating.

The corrosion experiments are ongoing along with hydrogen analysis of repository relevant coppers (i.e., electrodeposited, and cold spray copper). Preliminary results indicate that at this relatively low temperature of 75°C some of the hydrogen being released into the corrosion cells is attributable to hydrogen inside the copper as a result of its manufacturing processes as opposed to copper corrosion. While the relative amounts of hydrogen being produced are not yet definitively assigned, this work indicates that the extremely low corrosion rates being measured in the program are highly conservative. Therefore, the NWMO is well justified in its copper corrosion assessment, which asserts that the total anoxic copper corrosion would produce less than 0.25 mm of damage in 1,000,000 years and is consistent with the conservative NWMO total corrosion allowance of 1.204 mm over that period of time (Hall et al. 2021).

4.3.1.2 Microbiologically Influenced Corrosion

The repository environment is anticipated to evolve from early oxic conditions to later anoxic conditions. Likewise, degradation processes of the UFCs should transition from the initial oxygen-driven processes to those governed by the availability of sulfide as an oxidant. One feature of this transition is likely to be the conversion of any accumulated (hydr)oxide-type corrosion products produced during the oxic phase to copper sulfide compounds. This conversion is important for determining microbiologically influenced corrosion allowance. A preliminary assessment by (Hall et al. 2021) indicated that where high amounts of previously oxidized copper and high concentrations of aqueous sulfides are considered to occur simultaneously, it is presumed that only some (i.e., 50%) of the previously oxidized copper will convert to copper sulfide. To enhance the confidence of this assessment further investigations on the conversion process was initiated. Based on the recent investigations, during the conversion process, sulfide species could interact with the UFC surface in several ways such as a) chemical conversion, b) galvanically-couple process and c) direct corrosion. Results to date indicate a rapid and quantitative conversion of oxides according to processes a) and/or b), followed by direct corrosion of the Cu surface by sulfide (Salehi Alaei et al. 2023).

Under anaerobic conditions, microbiologically influenced corrosion (MIC) could occur, where sulfate-reducing bacteria produce bisulfide (HS^-) that can transport through High Compacted Bentonite (HCB) and corrode the copper barrier (Md Abdullah et al. 2022). This is an interdisciplinary phenomenon that includes processes such as microbial activity, species transport through the HCB as well as corrosion dynamics. A new experimental work initiated and focused on 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. Preliminary results indicate that geochemical reactions/sorption of HS^- onto HCB resulted in certain changes in the bentonite composition that may have caused unusual diffusion behaviour (Chowdhury et al. 2024*,* Rashwan et al. 2023). Further studies, including sample analysis (i.e., via SEM-EDS and total sulfur analysis) are underway to better understand the transport dynamics, and the results will aid in assessing the performance of EBS. In addition, it is anticipated that sorption (via adsorption and geochemical reactions) onto bentonite will reduce HS^- transport and minimize the risk of copper corrosion, therefore, a systematic study was conducted in laboratory batch experiments to investigate 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. The experimental results showed (Figure 4-16) that HS^- sorption onto bentonite increased with increasing temperature but decreased with increasing pH and ionic strength (Papry et al. 2023).

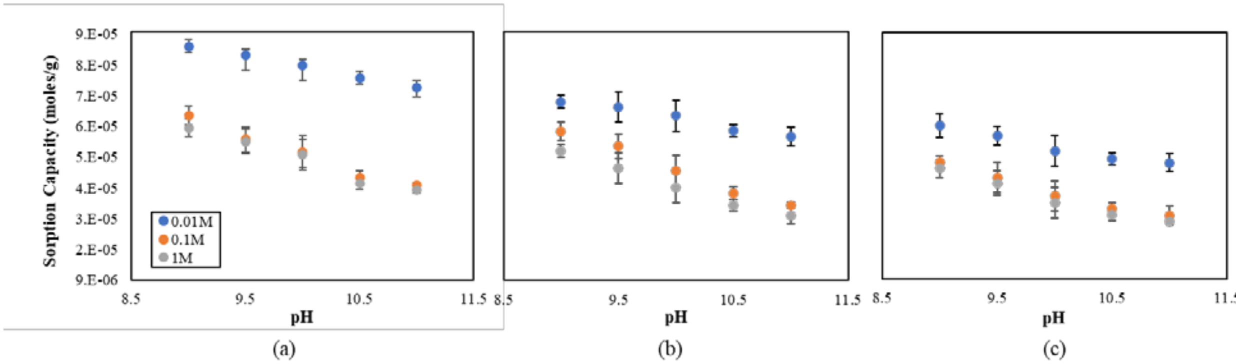


Figure 4-16: Effects of pH and ionic strength on HS⁻ sorption onto bentonite at various temperatures (a) 40˚C (b) 25˚C and (c) 10˚C. All data presented are the average of triplicate tests, with error bars showing the standard deviation.

4.3.1.3 Corrosion of Copper Coatings

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

- Short-term exposure of copper samples to aggressive conditions (under both humid and aqueous environments);
- Long-term exposures of copper samples to benign conditions;
- Electrochemical polarizations to simulate corrosion;
- Various exposures of galvanically coupled steel and copper samples to simulate
- damaged containers
- Comprehensive surface analysis to assess samples before and after the exposures noted above.

Despite more than 14 years of effort, little difference was found on samples from different fabrication methods. In these experiments, there is some evidence that cold spray copper samples undergo preferential dissolution at the grain boundaries only under aggressive and acidic conditions which are not expected in a DGR. The degree of the preferential dissolution varies with the amount of oxygen in the copper coatings, the temperature at which the heat-treatment was performed as well as the chemistry of exposure solution (e.g. aeration level and chloride). A few upcoming publications in peer-reviewed journals in 2024 will provide a comprehensive description of the most current understanding of copper coating corrosion.

4.3.1.4 Corrosion of Copper in Radiolytic Environment

The copper coated UFC will be exposed to a continuous flux of γ-radiation emitted from the decay of radionuclides in the used fuel. Although the γ-radiation does not affect the metal directly, any trapped water or humid air near the UFC will decompose to produce redox-active and acidic species that can affect the corrosion of the copper coating. 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 been developing such models lately (King and Behazin 2021) and is currently in the process of converting existing models and developing new coupled models using the commercial software package COMSOL Multiphysics (see Section 4.3.4.1). The code is designated the Copper Corrosion Model for Radiation-induced Corrosion (CCM-RIC) and the first phase of the work has been accepted for publications (Behazin et al., 2023). In addition to NWMO's modelling efforts, experimental work is underway as part of 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 included a series of irradiation experiments conducted by Jacobs 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. It is intended that the outcome of this project will help to answer a long-standing question regarding whether radiation dose rate is the key factor in radiation induced corrosion allowance or the total dose. This work package is expected to be completed by the end of 2024.

4.3.2 Microbial Studies

Following closure of the DGR, groundwater will slowly saturate the bentonite clay. While any oxygen present due to excavation will be consumed long before this, it is possible for hydrogen sulfide species, should they be present, to cause corrosion of the UFC. Since both remaining potential DGR host sites do not contain hydrogen sulfide in their groundwaters at DGR depths, the only potential source of the oxidant is due to microbiological activity. However, these microorganisms called sulfate-reducing bacteria (SRB) will only be viable should the environmental conditions allow it. With respect to the DGR, the bentonite clay ensures that SRB will not be viable by maintaining a low water activity (i.e., <0.96) and constricting pore spaces if the emplacement dry density exceeds 1.4 g/cm^3. While the HCB and the Gap Fill Material (GFM) is expected to have emplacement dry densities greater than 1.4 g/cm^3, work is being conducted to explore the viability of microbes in a range of dry densities to fully understand the nature of the microbes in clay. Of particular interest is the GFM which will have a dry density lower than the HCB.

Significant effort has been dedicated recently to optimizing the extraction and characterization of DNA held within the bentonite clay 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).

To supplement the in-situ work being performed in underground labs, pressure vessels (Figure 4-17 (a) and (b)) have also been designed, fabricated, and commissioned to perform many ex-situ experiments at Western University. In 2022, an initial set of scoping experiments was completed where GFM ranging from dry densities of 1.1 to 1.6 g/cm^3 were saturated with water for up to 18 months. Pressure cells were then disassembled and analyzed for microbiological taxonomy and cell abundance. Figure 4-14:(c) shows results for the starting material (i.e., time zero GFM) and GFM compacted to 1.25 and 1.6 g/cm^3. In all cases there is short term growth of aerobic bacteria which then become in active after about 12 months. For SRB at low densities some small growth is shown over short timescales while the higher density GFM supresses SRB growth over all timeframes. Results of this first campaign are currently accepted for publication in the Journal of Applied Microbiology (Beaver et al. 2023).

Following initial scoping tests, which occurred throughout 2020-2021, an anoxic testing campaign was initiated and is currently nearing completion. This experiment compares additional bentonite dry density conditions that more comprehensively bracket the range expected for DGR buffer boxes and GFM. Data collection and analysis is ongoing and includes a combination of cultivation-based and molecular (DNA-based) approaches. This experiment will allow for a direct comparison of oxic and anoxic pressure vessel incubations that collectively test for the broad range of possible microbial responses to the engineered barrier system of a proposed DGR environment.

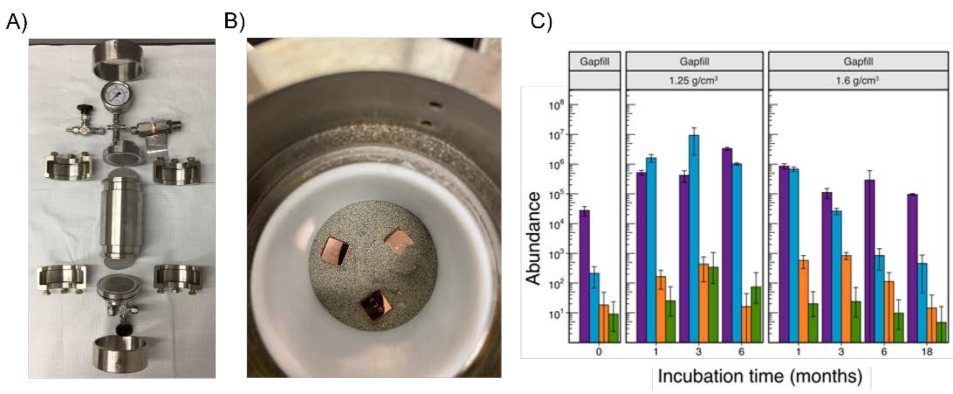


Figure 4-17: (a) Deconstructed Pressure Vessel for Ex-situ Microbiological and Corrosion Analyses; (b) View Diwn Inside a Pressure Cell Showing Copper Coupons and Bentonite (c) Abundances of Cultured Microorganisms from Pressure Cells Containing Uncompacted GFM and GFM with a Dry Density of 1.25 and 1.6 g/cm^3 versus Incubation Time.

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 an NWMO DGR, the presence of bentonite is expected to supress any such behaviour of sulfate-reducing bacteria.

4.3.3 Field Deployments

To compliment 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 are directed to evaluating the synergistic behaviour of copper embedded in bentonite deployed in DGR-like environments. This work utilizes so-called “module experiments” based on designs created by Nagra, the Swiss nuclear waste management organization; however, the NWMO has adapted these experimental methodologies and applied them in environments which more closely resemble potential Canadian DGR sites.

4.3.3.1 Ocean Module Retrievals

In 2022, twelve modules comprised of UFC materials encased in compacted bentonite were deployed at the Endeavor East site (water depth ~2,318 m with pressures of ~23.51 MPa). In continued partnership with Ocean Networks Canada (ONC) at the University of Victoria, the NWMO and academic partners at Western University and the University of Waterloo retrieved the first three modules in the July 2023 timeframe (see Figure 4-18 and Figure 4-19).. Additionally, water sampling was also performed that would go along with the modules for further study at the universities. These studies will examine the effects of such pressures and environment considered to be a reasonable analogue for the DGR (i.e., highly saline, low in oxygen and microbiologically active). Future retrievals will occur in 2024, 2025 and 2026.

Figure 4-18: Test module system at Endeavour East on seafloor upon arrival

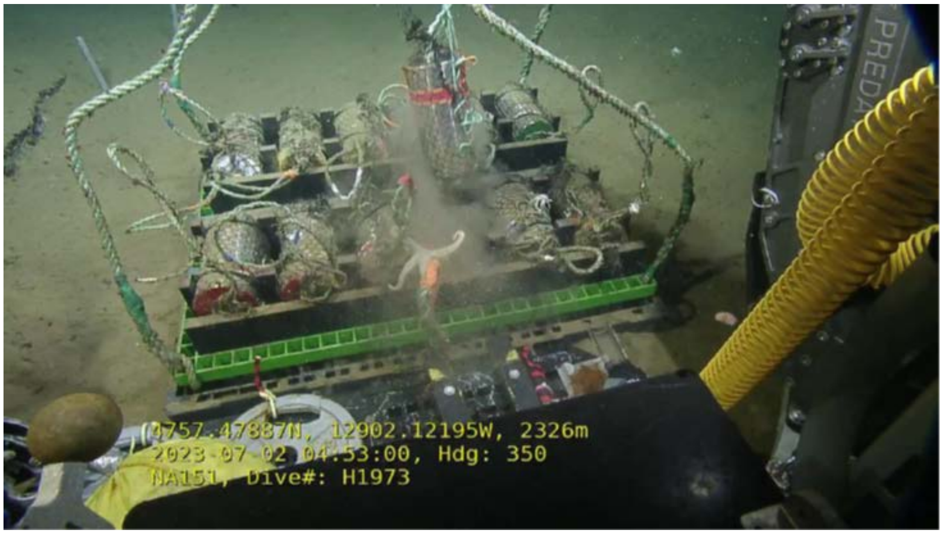


Figure 4-19: Retrieval of first module from the test module system with robot.

4.3.3.2 Ignace Borehole Retrievals and Deployments

In 2021, the testing system was implemented in the crystalline rock of the WLON-Ignace area for borehole IG_BH02 by Solexperts AG (Switzerland) (see Figure 4-20). In the September 2021 timeframe, six EBS modules were installed containing UFC materials encased in compacted bentonite at a depth of approximately 300 m which is considered a reasonable representation of a DGR environment in that it will be anoxic and contain water in this potential host rock. In October 2023, two modules were retrieved (Figure 4-21) and two new ones were deployed. Additionally, water samples were also taken from the borehole. The retrieved modules and water samples were then issued to Western University and the University of Waterloo, respectively for comprehensive corrosion and microbiological analyses. Modules will remain in the borehole for up to a decade (since 2021) with planned retrievals/deployments approximately every two years. The results are expected to contribute greatly to the understanding and confidence in the engineered barrier system.

Figure 4-20: View of the site showing the office trailer, storage trailer, and purpose designed truck.

Figure 4-21: Successful retrieval of one module.

4.3.4 Corrosion Modelling

4.3.4.1 Radiation Induced Corrosion Modelling

As with other components of the disposal system, it is necessary to make predictions of the long-term copper corrosion behaviour of the UFC including the effects, if any, of radiation induced corrosion (RIC) in a deep geological repository (DGR). The development of a RIC model for copper containers builds upon previous work developing mixed-potential copper corrosion models (CCM). The Copper Corrosion Model (CCM) predicts the uniform (general) corrosion behaviour of a copper-coated UFC in a deep geological repository (DGR). The model is generally applicable and is capable of describing the corrosion behaviour of copper in any O_2-containing Cl^- environment in which mass transport of species to and from the corroding surface occurs by diffusion. In its current form, the model is one-dimensional (1-D) which makes it robust and applicable to a range of container and DGR designs. The strength of the CCM is that it is mechanistically based and was developed in conjunction with an expensive experimental program of electrochemical and corrosion studies (King and Kolář 2000, 2006).

The CCMC is used as a basis for the additional coupling of the anodic reaction of copper to the reduction of radiolysis products expected in a DGR environment. Building the model in a stepwise approach is required, adding complexity and validating to each component. In 2023, the overall conceptual model of a copper corrosion model for radiation induced corrosion (CCM-RIC) was introduced including the use of the commercial discrete solver COMSOL-Multiphysics. An initial bulk radiolysis model was developed and validated including comparison with experimental data reported in the literature (Behazin et al. 2023).

4.3.4.2 Localised Corrosion Modelling

The development of a mechanistic model of pitting under an Evans droplet during the early aerobic phase of the DGR including the hysteresis effects of the drying and re-wetting of the copper coated container was initiated in 2020 with work on-going in 2023. During this early aerobic, unsaturated phase in the DGR it is expected that the corrosion mechanisms are similar to atmospheric corrosion, involving the deliquescence of surface contaminants, droplet formation, secondary spreading and spatial separation of anodic and cathodic processes due to the geometry of the droplet.

Work being conducted at the University of Florida to develop a finite-element model with the means to predict, mechanistically the rate and extend of localized damage due to copper corrosion (You et al. 2023).

4.4 PLACEMENT ROOM SEALS AND OTHERS

4.4.1 Reactive Transport Modelling of Concrete-Bentonite Interactions

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

In 2022, MIN3P-THCm was used to investigate long-term geochemical interactions driven by diffusion-dominated transport across interfaces between bentonite, concrete and host rock (limestone and granite) in the near field of a repository. Due to the relatively high pH of pore water in concrete, substantial mineral dissolution and precipitation has been predicted to occur at the bentonite/concrete and/or concrete/host rock interfaces, leading to porosity reduction or even pore clogging in close proximity (<1 cm) of the interfaces (Xie et al. 2022, 2021). The impact of altered interfaces on the migration of radionuclides (i.e., I-129) has also been numerically investigated. Depending on the rate of porosity reduction relative to the timing of radionuclide release from a canister defect, the one-dimensional simulation results indicate that pore clogging could significantly inhibit radionuclide migration (Xie et al. 2022, 2021).

MIN3P-THCm was also applied to simulate the CI-D (tracer diffusion across 10-year old concrete-claystone interface) long-term diffusion experiment at the Mont Terri underground research laboratory. An anisotropic diffusion model for unstructured grids was implemented in MIN3P-THCm and verified against a three-dimensional analytical solution. The model was then applied to simulate the in-situ diffusion experiment in three spatial dimensions while honouring the complex geometry created by the vertical drill hole, the inclined test hole, the concrete-clay interface, the anisotropic Opalinus Clay (OPA), and the thin ‘skin’ layer between the concrete and the OPA. Simulation results show that long-term tracer diffusion is enhanced parallel to the bedding due to the anisotropic properties of OPA in comparison to the case without considering anisotropy (Su et al. 2022a and b).

4.4.2 Gas-Permeable Seal Test (GAST)

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

GAST field experiment was delayed due to a major leak event occurring in 2014 followed by a very slow saturation process in the sand bentonite mixture. At the end of 2021, the long-lasting saturation process completed and preparation work for a full-scale gas flow test was underway immediately. Starting from May 2022, the Gas Flow Test (GFT) was initiated with injection of a gas mix of 2% He and 98% N_2 to establish and characterize the gas flow path. Gas flow through the sand/bentonite mixtures was confirmed by tracer detection, increase in storativity and TDR (time-domain reflectometer) data. Following the cleaning with pure N_2, a second round of injection of gas mix consisting of 10% He, 15% Ar, 0.1% Xe and around 75% N_2 was launched in 2023 to investigate the behavior of gases with different masses inside the experiment. The main Gas Flow Test was completed by the end of 2023 after another successful cleaning with pure N_2. The various data sets are currently being analyzed and summarized in a series of technical reports.

In 2019, a smaller scale, well instrumented laboratory experiment - mini-GAST was initiated at UPC (Polytechnic University of Catalonia), Barcelona, Spain. The mini-GAST project aims to mimic the GAST experiment in a much better controlled fashion in the lab within a much shorter testing time frame. The mini-GAST experiment comprises of two semi-cylindrical shape mock-up tests, MU-A (50 cm in length and 30 cm in diameter) and MU-B (1/3 size of MU-A). By the end of 2023, multiple lab experiments with both MU-A and MU-B were completed. UPC is currently working on the final report which summarizes all lab experiments.

4.4.3 DECOVALEX Modelling

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

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

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

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

The task is divided into three steps:

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

Step 1: FE heating phase: Modelling the change in pore pressure in the Opalinus Clay as a result of heating in the FE experiment. This requires 3D THM simulations with representation of partially saturated conditions. It includes three sub-steps: predication, analysis and calibration. Initially the 3D model was tightly specified to continue to build confidence in the model implementations (Step 1a). The results of Step 1a were compared to the data from the FE-experiment without the teams seeing the data. The teams were then provided with a sub-set of the data from the FE-experiment and invited to consider how best to use the large dataset for model comparison (Step 1b). Teams were then asked to use the data provided to calibrate their models, only changing material property values rather than adding features or processes to their models (Step 1c).

Step 2: FE ventilation phase: Modelling of absolute pressures in the Opalinus Clay, which will require representation of the ventilation of the FE tunnel prior to heating. In Step 2 the restrictions of the specification were removed and teams were asked to update their models with additional features and processes as well as calibrating parameters to try and improve the fit of the models to the data. Teams were encouraged to represent ventilation of the open FE tunnel prior to backfilling with heaters and bentonite and in Step 2, the absolute pressure in the Opalinus Clay is compared between the teams. In Step 2, modelling teams can choose the complexity of the representation of excavation and EDZ development.

Step 3: Step 3 was an opportunity for teams to use the models developed in Step 1 and Step 2 to make predictions about the temperature and pressure changes that will be expected at the FE experiment over the next few years in light of the planned changes in thermal output of the heaters.

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 are compered between different teams and compared with measurements. These models of these modelling teams are able to reproduce the correct range of behaviour for temperature and pressure evolution in the Opalinus Clay, but it has been challenging to achieve a close match between all the teams and the data. The document for these comparisons between different teams and comparison with measurements is under preparation as a final DECOVALEX report.

The NWMO performed all of these modelling and obtained results which well aligned with most of international modelling team’s results and with measurements. Part of NWMO modelling work in Step 1 has been prepared to a draft journal paper (Guo and Briggs 2024).

4.4.3.2 DECOVALEX 2023 Task F: Performance Assessment

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

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

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

In 2023, Task F was completed including benchmarking of the various software programs and performance assessment tools used in Task F against hydrogeological flow and transport problem with known analytical solutions. The NWMO performed these benchmarks with the Integrated System Model (see Section 6.4.2.2.1) and its constituent codes COMSOL and HydroGeoSphere.

At present the generic crystalline rock 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 report will be published in 2024.

4.4.4 Shaft Seal Properties

In 2023, the NWMO completed the testing program (Dixon and Stone, 2023) that identified an optimized shaft seal mixture by evaluating the behavior of bentonite:sand blends having composition ratios other than 70:30. In this study, the use of a crushed limestone sand was examined in addition to granitic sand. Composition ratios of bentonite:sand of 50:50, 60:40, 70:30, 80:20 and 90:10 (by weight) were assessed by using two different salinity fluids, CR-10 (TDS 11 g/L) and SR-Sh (TDS 325 g/L), approximating groundwater conditions for crystalline and sedimentary sites, respectively.

The tests evaluated the following:

- Compaction/fabrication properties of the materials (to Modified and Standard Proctor density)
- Consistency limits (Atterberg Limits) and free swell tests
- Moisture content and density of fabricated material
- Mineralogical/chemical composition, including measurements of montmorillonite content
- Swelling pressure
- Saturated hydraulic conductivity
- Two-phase gas/water properties, specifically the capillary pressure function (or soil water characteristic curve, (SWCC)) and relative permeability function, measured over a range of saturations that include the fabricated and fully saturated condition
- Mineralogical/chemical composition of the materials exposed to brine for an extended period of time

The test results indicate that for low salinity groundwater conditions (CR-10), compaction to 98% of the Standard Compaction Maximum Dry Density or 95% of Modified Maximum Dry Density of the bentonite/sand mixtures studied will be sufficient to achieve the swelling pressure and hydraulic conductivity targets (>100 kPa and <10^{-10} m/s, respectively). There was no clear improvement in effective montmorillonite dry density (EMDD) once bentonite content exceeded 60%. Under high salinity conditions (SR-Sh), none of the materials compacted to 98% of Standard Compaction Maximum Dry Density met the Ps and k requirements for shaft backfill (<100 kPa and <1E-10 m/s). Materials compacted to 95% of Modified Compaction Maximum Dry Density achieved targeted Ps and k behaviour. There was no discernible effect of aggregate type on the hydraulic conductivity of any of the bentonite-sand blends examined in the study. However, it was observed that the swelling pressures with the crushed limestone at low density were slightly lower than those with the granitic sand. Since this was based on a very limited number of data points, it was not conclusively indicative. A larger database should be developed to confirm this phenomenon as it was not evident in the hydraulic conductivities measured for these same specimens.

In the study, the mineralogical or chemical composition of MX80 bentonite soaked in low salinity (CR10) and high salinity (SR-Sh) groundwaters were examined for changes. Bentonite samples were analysed following 54 and 82 months of testing. There was no discernible change in the mineralogical composition and the chemical composition remains similarly unchanged except for elevated Ca and K and reduced Na contents that developed soon after soaking of clay was started. These changes are attributable to cation exchange on the montmorillonite clay surfaces with Na being lost to Ca and K being gained from the groundwater.

Soil water characteristic curves (SWCC) and gas permeability values were generated for potential shaft backfilling materials. These values will provide reference values for use in numerical modelling.

4.4.5 Tunnel Seal Properties

The current tunnel seal concept includes two bentonite-based sealing materials, Dense Backfill (DBF) and Gap Fill Material (GFM). Dense Backfill (DBF) 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 DBF particularly in the areas close to tunnel walls and roof, it is assumed that DBF will be installed in horizontal layers until it has reached a level where compaction is no longer possible. The remaining volume between the DBF and the roof will be filled with GFM.

The basic swelling pressure and hydraulic conductivity requirements for the DBF are as follows:

- Swelling pressure (or pressure at contact between DBF and its confinement (rock or concrete structures) should be >100 kPa),
- Hydraulic conductivity needs to be $<10^{-10}$ m/s,
- Sedimentary DGR will require use of limestone aggregate and functioning of DBF at high groundwater TDS (e.g., SR-290),
- Crystalline DGR will require use of granitic aggregate and assumes the presence of a low TDS groundwater (e.g., CR10), and
- When estimating Ps and k, it assumed that the EMDD concept is applicable to DBF

In 2023, the NWMO initiated a testing program to (1) optimize the DBF blend for both reference groundwaters so as to meet interface contact pressure design requirements and (2) fully characterize the components of the DBF specified for compaction properties.
The initial DBF blend examined composed of graded aggregate (crushed limestone and granite), MX-80 bentonite and glacial lake clay used as an inert filler.

The compaction results indicate that:

- in a highly saline environment, the bentonite content more than 40% requires in order to meet the design requirements.
- in a low salinity environment, the bentonite content 30% meets the design requirements.
- the use of lake clay as a component of the DBF did not result in an improvement in swelling pressure and hydraulic conductivity.

Based on the compaction test results, new DBF mixture ratios (bentonite content up to 40%) 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).

4.4.6 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 in the optimization and material property are provided in NWMO-TR-2021-20 (NWMO 2021a).

Upon completion of the LHHPC testing program, a new testing program was initiated 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.

In 2022, 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, and laboratory tests with these cells were prepared, including preparation of two reference waters (CR-10 and SR-290) in 2023. The tests will be initiated in the second quarter of 2024.

4.4.7 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).

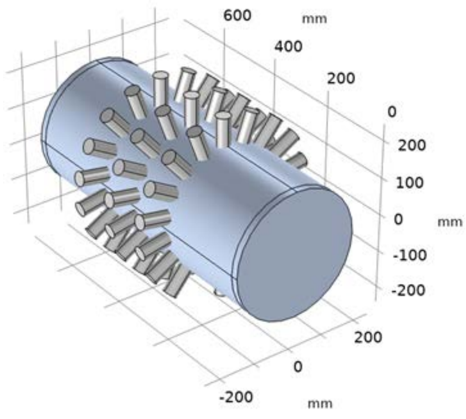
In 2022, the NWMO continued to use fully coupled Thermo-Hydro-Mechanical (THM) CODE_BRIGHT models to study the unique NWMO placement concept. The previous numerical modelling was focused on the evolution of the bentonite-based materials in the crystalline rock geosphere (CR-10). In that year, the effect of the sedimentary rock geosphere (SR-290) on the evolution of the materials was numerically assessed. The major change in the numerical modelling was an increase in groundwater salinity.

The results obtained from the numerical modelling of an emplacement room in sedimentary rock indicated faster saturation than that of a similar room in crystalline rock, as the increased salinity would increase the bentonite hydraulic conductivity. As shown in Figure 4-18, the computed density field for the sedimentary rock case was more heterogeneous than that for the crystalline rock case. The results also indicated that an increase in salinity would reduce swelling pressure of the bentonite and consequently, result in less homogenization of bentonite density.

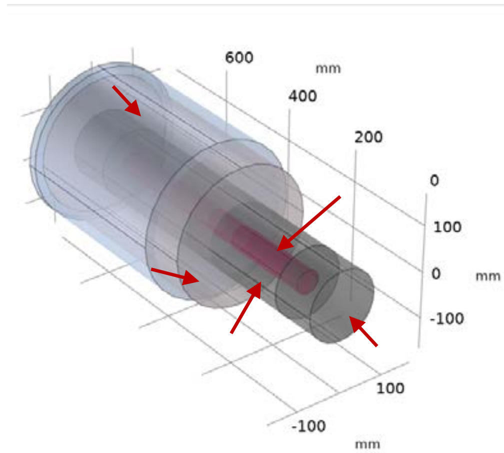
In 2023, the NWMO prepared a technical report on the numerical modelling work previously done by the Clay Technology group to be published in 2024.

4.4.7.1 Coupled Thermo-Hydro-Mechanical Benchtop Experiments

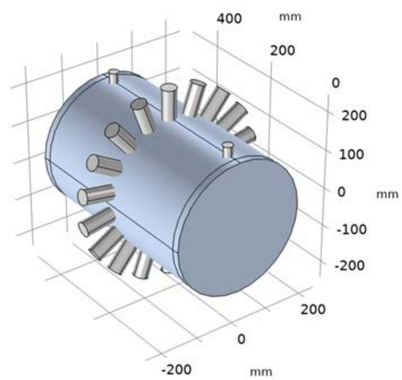
In late 2018, the NWMO and its contractor (the National Research Council of Canada) launched a work program to design and construct test cells to perform experiments examining the Thermal-Hydro-Mechanical (THM) response of HCB and GFM for use as a component in the Engineered Barrier System of the multibarrier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



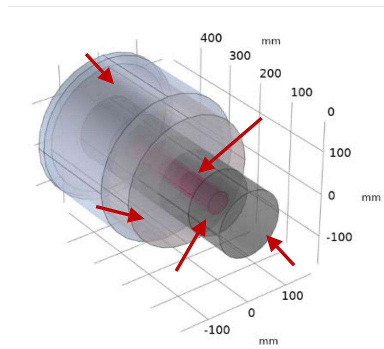
1 3D isometric view of the T apparatus



2 3D schematic of the T apparatus



3 3D isometric view of the THM apparatus



4 3D schematic of the THM apparatus

Figure 4-22: Representative Schematic of the T and THM Test Apparatuses

Two cylindrical experimental cells were manufactured; one to measure the THM response of HCB and GFM when exposed to a temperature boundary condition (called T apparatus) and the other to measure the THM response when exposed to both temperature and hydraulic boundary conditions (called THM apparatus). Figure 4-21 shows a representative schematic of the T and THM apparatuses.

In 2022, 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. In 2023, a new water pump system for the THM test was specified and ordered, based on the NWMO recommendation. The contractor also prepared a power meter and temperature controller for both the T and THM tests. These heating-related units were specified for future numerical modelling. The T test will be conducted in the second quarter of 2024.

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.

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.

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.

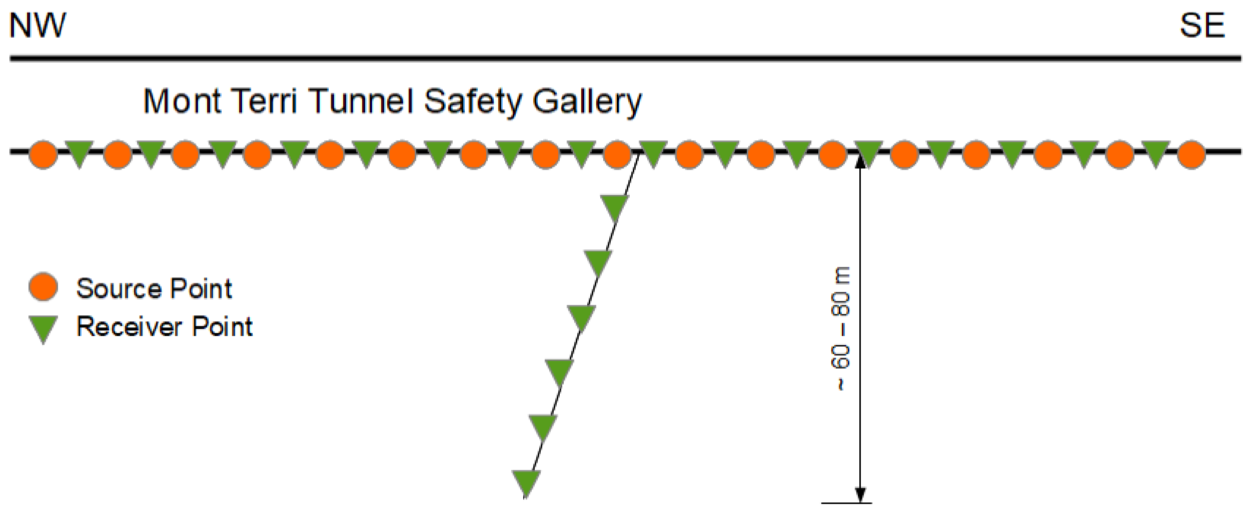


Figure 5-1: Conceptual Sketch of Seismic Acquisition Along the Safety Gallery in the Mont Terri Tunnel (cross-section, not to scale).

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). It was proposed that the two deep boreholes drilled at SON/South Bruce for the DGR Project will be sampled and the results added to this study.

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

The results will be 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 are 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 to be collected as part of this new work scope. REE’s are 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 will be 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 are currently under analysis by the University of Windsor and results will be delivered in late 2024.

The results will be 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.

5.1.1.2.2 Clumped Isotope Paleothermometer for Dolomite

A research project was initiated in 2021 with the GSC and NRCan that aims to use a new approach to assess fluid longevity within carbonate sedimentary rock mass. The clumped-isotope thermometer is a relatively new geothermometer which functions on the principle that rare 'heavy' isotopologues in a molecule prefer to bond together, with a dependence on the temperature of the system. Specifically, ^{13}C and ^{18}O in a carbonate mineral are thermodynamically ordered or 'clumped' depending on the temperature of the depositional environment. Determining the abundance of clumped isotopes in carbonate (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. Using clumped isotopes analysis of carbonates as a tool, and with the objective of establishing a new paleothermometer for dolomite as well, key aims of the research program will be to reappraise the evolution of the Ordovician limestone sedimentary units in Southern Ontario and provide additional insights on the origin of mineralising fluids and post-depositional modifications to these rocks.

During 2021 and 2022, key accomplishments included: 1) hiring of an experienced staff member to help lead this 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 a manuscript for publication in a scientific journal, and 7) analysis of materials from the Bruce nuclear site was initiated.

In 2023, the manuscript initiated in 2022, 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, with the aim to publish in 2024.

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

Ongoing research by the United States Geological Service (USGS) will continue to investigate the underpressures shales within the SON/South Bruce Site. This work program extension will investigate: (1) a hypothetical rock-wellbore system that will consider various hypothetical initial gas phase distributions and pressure profiles to study evolution of the system after the borehole is drilled and shut in. The area surrounding a single borehole will be simulated over time scales representing measurement periods in the field. The results will be used to examine how pressures measured in boreholes relate to liquid pressures in the rock when separate phase gas is present (2) the South Bruce site. Since the Cambrian is absent at the South Bruce site, our model will necessarily also lack it. They will then perform simulations 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 will then be used to draw conclusions, which will be disseminated to the scientific community via presentations and journal articles.

In 2023, the research was extended to consider whether the observed underpressures can be modelled in the case where the Cambrian sandstone, at the base of the Pleozoic strata, is not present.

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 corrosive 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, 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 suggest 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 2022-2023, the Canadian Shield component of the database was advanced (including thousands of data points). A journal article documenting new observations arising from the compilation of the database was prepared for publication late in 2023 and the final database (containing data from various locations in the Canadian Shield) will be published to a data repository for scientific use. The article and database are anticipated to be published in 2024.

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 current research are to 1) develop and optimize a method to fully extract porewater from intact crystalline core samples, and 2) benchmark the approach using suitable core material saturated with water of known isotopic composition. Through repeated re-saturation and extraction experiments, it became clear that extraction of porewaters from low-permeability and low water content crystalline cores was possible without fractionation, but that artifacts of the re-saturation process caused isotopic depletion in the re-saturation porewaters. Over 2021-2022, a mechanism to fully re-saturate the cores for benchmarking was developed, such that the re-saturated porewaters were not accompanied by fractionation during the re-saturation process. Testing of several different approaches to re-saturate core followed, from which it was determined that re-saturation using a combination of high vacuum (45 mTorr), followed by heating (120°C) at elevated pressure (15 PSI), for long durations, produced high levels of saturation with no significant isotope fractionation, as shown in Figure 5-2.

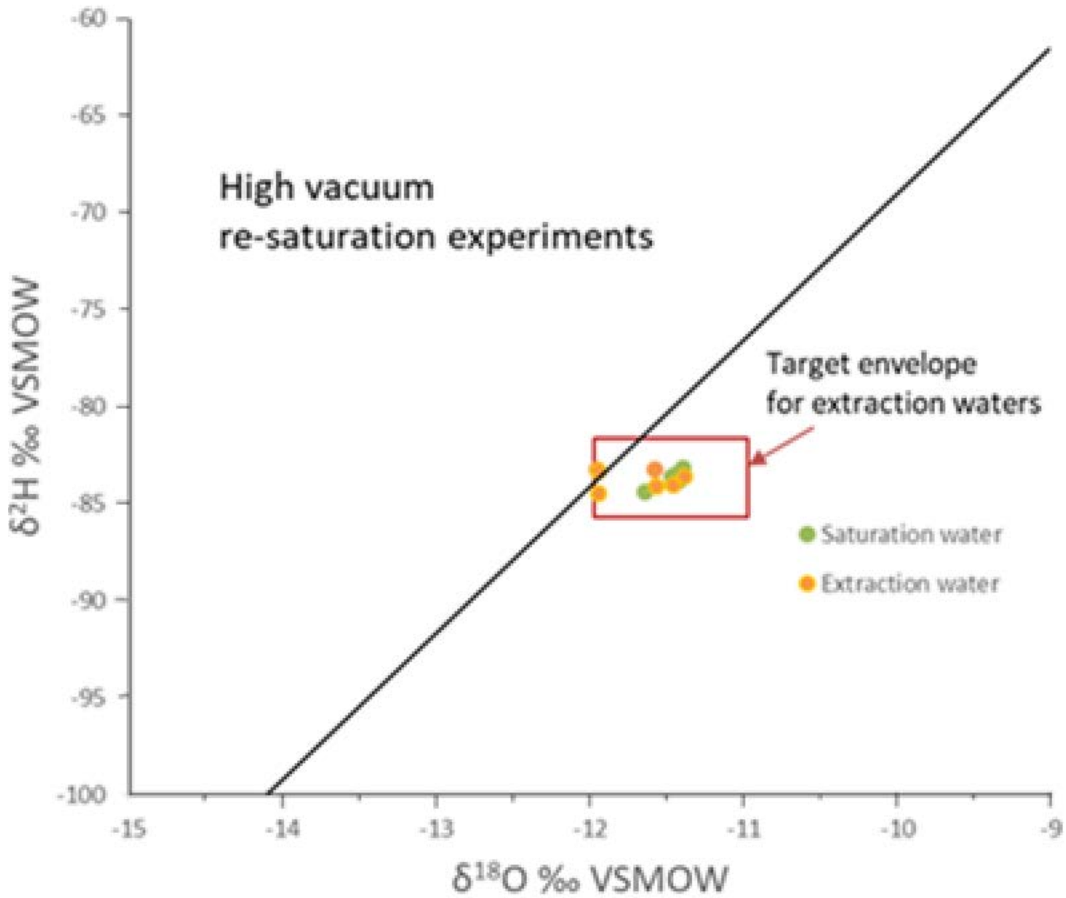
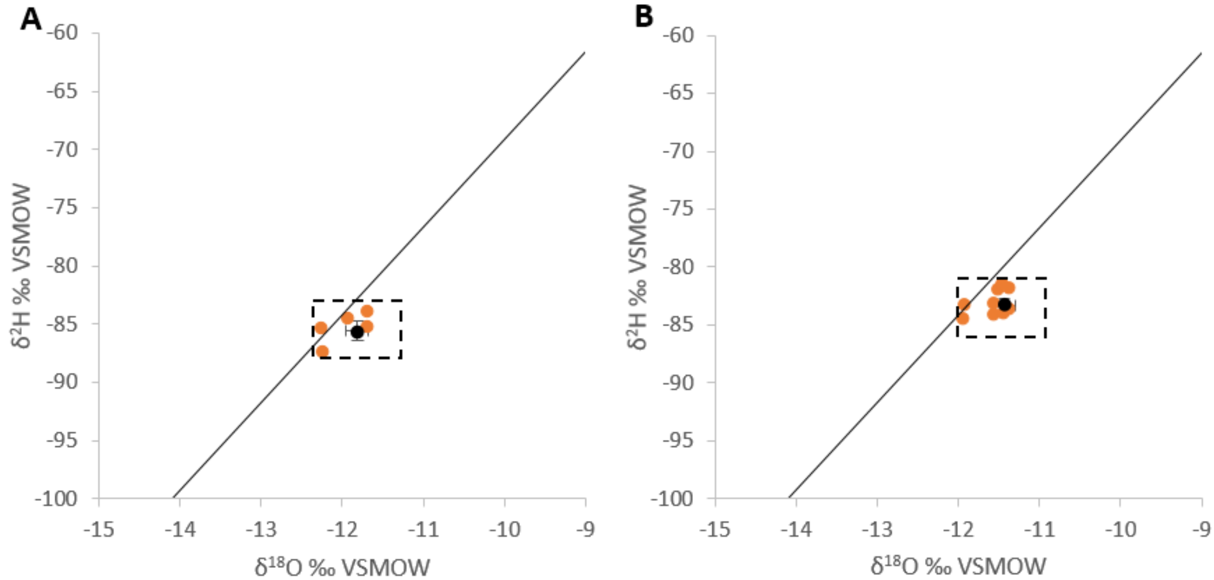


Figure 5-2: Isotopic Composition of Porewaters Extracted from Crystalline Rock Using Re-Saturation Protocols that Produce Porewaters Essentially Free of Re-saturation Artifacts

For porewater extraction experiments using this protocol, close to 100% of the re-saturated water mass could be recovered by distillation at 150°C. Additional experiments were carried out to test the efficiency of porewater extraction at 120°C. The advantage of using the lower extraction temperature is to prevent the possible release of fluid-inclusions, which may otherwise influence the interpretation of the isotopic composition of the porewater. Extractions carried out at 120ºC yielded comparable porewater recoveries to those carried out at 150ºC (100±1.55%, n=5 vs. 99.70±0.54%, n=9, respectively). Figure 5-4 shows $\delta^{18}O$ vs. $\delta^{2}H$ of the porewaters extracted at 120ºC (Figure 5-3A) and 150ºC (Figure 5-3B) plotted with respect to the local meteoric water line for Ottawa. The $\delta^{18}O$ and $\delta^{2}H$ of the recovered porewaters at 120ºC fall within the acceptable error range of ±0.5 and ±2‰ for the isotopes, respectively (Figure 5-3). Therefore, a temperature of 120ºC can be used to fully recover porewaters from crystalline whole-core samples without artifacts or isotope fractionation.



Notes: Left chart (A): Extraction Experiments Carried Out at 120 ºC. Right Chart (B): Extraction Experiments Carried Out at 150 ºC. Each Orange Data Point Corresponds to a Single Experiment. Black Points with Error Bars Correspond to the Average of $\delta^{18}O$ vs. $\delta^{2}H$ of the Saturating Water (± Standard Deviation). The Dashed Square Represents the Target Acceptable Envelope for Extraction Waters. The Solid Line Represents the Local Meteoric Water Line (LMWL) for Ottawa, Ontario, Canada.

Figure 5-3: δ18O vs. δ2H of Porewater Extracted from Whole-Core Samples

The success of the developed methodologies to saturate and fully extract porewater from whole-core samples, without isotopic fractionation, allowed for further testing using a synthetic saltwater solution (SSW, 1 mole/L NaCl and 0.05 mole/L KBr, 2x relative to seawater) to saturate whole-core samples. This approach allows for determining 1) the impact of ions/salts on the recovery of porewater, and 2) whether it is possible to reconstruct the geochemistry of the recovered porewater. The results have revealed that saturating crystalline whole-cores with SSW did not influence the extraction efficiency with vacuum-distillation, as 97-100% of the water was recovered. Therefore, porewaters from fresh, fully saturated crystalline cores can be fully extracted without artifacts using the extended extraction method. In addition, aqueous leaching of solutes from post-vacuum-distilled core samples can be confidently used to reconstruct the geochemistry of the porewaters.

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 (Ignace, Ontario, Canada). 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 will be published early in 2024.

5.1.3.3.2 Porewater Extraction – Sedimentary Rocks

Continuing work at the University of Ottawa focuses 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 our 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.

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 focuses on the H- and O-isotope compositions of clay minerals in Ordovician shales from the Bruce Nuclear Power Generating Station (“Bruce Site”) to try to understand the impact of these processes. Previous key findings this work include: 1) abundances of illite > kaolinite > chlorite comprise the <2μm fraction of these shales; 2) the clay mineral H- and O-isotope compositions plot to the left of terrestrial clay weathering lines in H- and O-isotope space; 3) calculated water H- and O-isotope compositions in equilibrium with these clay minerals at maximum burial temperatures (~90°C) match porewater H- and O-isotope compositions measured by three techniques; and 4) apparent H-isotope clay mineral-water exchange (0.4-3%) occurred in 10-week experiments at 68°C. These preliminary data suggested that isotopic exchange with clay mineral structural H can modify porewater H-isotope compositions in low water-content shales.

In 2023, several tasks were advanced or completed, and are summarized below.

1. Oxygen isotope data collection for <2µm clay-size fraction samples was completed using 8-week duration exchange experiments. The results include data for Clay Minerals Society (CMS) standards (chlorite, kaolinite, smectite, illite), as well as samples of Queenston, Georgian Bay and Blue Mountain shales, and the Cobourg argillaceous limestone, from the Bruce Site. Experiments using light and heavy isotope exchange waters were conducted at 90, 120 and 150°C for all samples. The oxygen-isotope results confirmed preliminary indications of unexpectedly high amounts of oxygen-isotope exchange in the clay-water system, which increases with increasing temperature.

2. Similar experiments were conducted and completed on powdered, whole-rock samples from the Queenston, Georgian Bay and Blue Mountain shales, and the Cobourg argillaceous limestone. Experiments were conducted at 70, 90 and 120°C. In these experiments, the silicate fraction was analyzed for O- and H-isotope compositions before and after the exchange experiments, as was the carbonate fraction (essentially calcite) for C- and O-isotope compositions. These experiments were designed to test whether whole-rock samples exhibit similar amounts of isotope exchange as the <2µm size-fraction. The results suggest that the hydrogen-isotope exchange is largely driven by the clay minerals, as expected, but that calcite present in the whole-rock samples also contributes significantly to oxygen-isotope exchange. A technical report describing the 8-week experiments is being prepared and will be published in 2024. This report will outline the significance of these data for possible modification of porewater oxygen- and hydrogen-isotope compositions in the Ordovician shales and argillaceous limestones of southern Ontario.
3. Twenty- and forty-six (46) week oxygen- and hydrogen-isotope exchange experiments at 90°, 120° and 150°C of <2µm size-fractions were undertaken in 2023 (and finishing in February 2024) for the Queenston, Georgian Bay and Blue Mountain formations for which the 8-week experiments were performed. These experiments are intended to evaluate the rate of isotopic exchange during clay mineral – water exchange in the Ordovician formations. The results should provide further insight into the extent of isotopic exchange expected in the Ordovician shales over geological time.
4. One suite of samples is undergoing isotopic exchange with isotopically labelled synthetic brine. A Na-Ca chloride brine of similar salinity and major ion composition to naturally occurring brines in the Ordovician units of southern Ontario is being used for this purpose, based on the Na+, Ca2+ and Cl- concentrations proposed by Yang and Kennell-Morrison (2021).

This work will be presented in a separate report to be prepared in 2024, which will incorporate key findings from the 8-week experiment report (noted above).

The Thermogravimetric Analyzer (TGA) – Cavity Ringdown Spectrometer (CRDS) instrument is well under development since the arrival and construction of the CRDS in summer of 2022. The system has the potential to release, capture and analyze the hydrogen- and oxygen-isotope compositions of free, bound and hydroxyl group water in rocks. Assembling the system and making it functional was a priority in 2023, as well as development of the physical interface between the TGA and CRDS. A procedure was developed in 2023 for conversion of raw isotopic data obtained from the TGA–CRDS system to VSMOW-SLAP calibrated values for water δ18O, δ17O and δ2H. This is a major step forward in achieving both precision and accuracy of the results. The analytical approach still requires refinement to achieve the accuracy and reproducibility possible for water using other methods. Systematic testing and benchmarking of the system will take six to twelve months and was initiated late in 2023.

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

The final NEA CLAYWAT Project report was formally submitted to the NEA for publication in 2023.

5.1.3.6 Porewater Gases - Mont Terri PC-D Experiment

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

Over the course of 2020, due to delays associated with the global COVID-19 pandemic, emphasis was placed on experimental planning and establishing a drilling contract for an experiment-specific borehole. In September 2021, the PC-D borehole (BPC-D1) was drilled, parallel to being in the lower shale facies, with five regularly spaced sampling intervals over its 20-m length. Samples for noble and non-inert gases were collected adjacent to one another in each sampling interval for the three participating laboratories (Hydroisotop GmbH, University of Ottawa and GFZ Helmholtz – supported by BGR), as well as complementary samples for porewater chemistry analytics (to be run using the absorptive paper method). 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 will complete analyses by mid-2024. The analytics, data compilation (including review and comparison of relevant noble and non-inert gas data from within the lower shale facies in other experiments at the Mont Terri URL) and overall findings of the comparison study will be prepared for publication in a Mont Terri Technical Report late in 2024.

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 2023, work as a part of GD was focused on the following projects: 1) stepwise high-pressure squeezing and pore fluid extraction / analyses, 2) redox and the role of Fe-containing minerals in controlling system Eh, 3) assessment of trace elements in porewaters, and 4) nitrogen-system dynamics in clay media.

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 LdBG

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.

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 Fm shale and the data demonstrate that beam hardening effects are virtually eliminated.

Work in 2023 focused primarily on advancing the X-ray fluorescence technique, which has potential for experimental monitoring of diffusion and reaction processes with a diverse range of tracers (e.g., I- and Cs+ can diffuse and be monitored simultaneously) that are of interest for evaluation of transport and attenuation properties in the near field. The use of multiple tracers simultaneously could allow lab-scale observation / evaluation of competitive ion-exchange, which is relevant for process upscaling and solute transport modelling. To date, X-ray measurement techniques have been developed using 2D and 3D imaging modes, radiography and computed tomography, respectively, and spectrometry mode (absorption and fluorescence).

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 expect; 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.

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). A CI/CI-D modelling meeting was taken place in May 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 from 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 will be analysed for CI in 2024 to assess 1) mineralogical alteration and the extent of alteration zones, and 2) the evolution of porosity.

5.1.4.3 Sorption

Sorption is a mechanism for retarding sub-surface radionuclide transport from a DGR to the environment. The NWMO has initiated the development of a sorption distribution coefficient (K_d) database for elements of importance to the safety assessment of a DGR (Vilks 2011). This initial database was further developed to include sorption measurements for Canadian sedimentary rocks and bentonite in saline solutions (with ionic strength *I*=0.23-7.2 mol/kgw (M)) including a reference porewater SR-270-PW brine solution (Na-Ca-Cl type with *I*=6 M) (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 (*I*=0.1-6.0 M) including SR-270-PW, as well as on granite and bentonite in Ca-Na-Cl solutions (*I*=0.05-1.0 M) including a reference groundwater CR-10 (Ca-Na-Cl type with *I*=0.24 M), under reducing conditions. The effects of ionic strength and pH (3-10) on the sorption of Se(-II), Tc, Eu and U(VI) on shale, illite, limestone, bentonite and granite have been investigated (Walker et al. 2022; Yang et al. 2022; Racette et al. 2023; Zheng et al. 2024). It was found that sorption of Se(-II) on illite and MX-80 showed little ionic strength dependency in *I*=0.1-6 M Na-Ca-Cl solutions. Sorption of Se(-II) on shale at low ionic strength (0.1 M and 0.5 M) was greater than those at higher ionic strength (1-6 M). Sorption of Se(-II) on granite and MX-80 in *I*=0.05-1.0 M Ca-Na-Cl solutions followed the trend of anionic sorption, with a decrease in K_d values as the solution pH increased. Sorption of Se(-II) on granite decreased as the ionic strength increased from 0.05 M to 1.0 M in Ca-Na-Cl solutions (Racette et al. 2023). Sorption of Eu on MX-80 was not affected by the ionic strength in *I*=0.5-6 M Na-Ca-Cl solutions, while sorption at *I*=0.1 M is greater than those at *I*=0.5-6 M (Yang et al. 2022). The two-site protolysis nonelectrostatic surface complexation and cation exchange sorption (2SPNE SC/CE) model successfully predicted the sorption of Eu, Se(-II) and U(VI) on MX-80 and illite, and the optimized values of surface complexation reaction constants were estimated (Yang et al. 2022; Racette et al. 2023; Zheng et al. 2024). The sorption of Pd on montmorillonite and sorption of Se(-II) on biotite in Ca-Na-Cl saline solutions are being studied using a combination of batch experiments, sorption modeling and DFT (Density Function Theory) calculations to explore the sorption mechanisms. Biotite is a common but minor mineral component of granite which is considered to dominate the sorption of some radionuclides.

Sorption of Se, Tc, Np, U and Eu were measured on biotite granodiorite tonalite, amphibolite and diabase dyke rock samples collected from boreholes in the Ignace area in reference groundwaters CR-10, CR-10NF (CR-10 in equilibrium with bentonite and carbon-steel container) and CR-0 (Na-Ca-HCO_3 type water with *I*=0.007 M) under both oxidizing and reducing conditions (Nagasaki 2022). The measured sorption K_d values will be used to update the NWMO sorption database for use in the safety assessment.

5.1.4.4 Surface Area & Cation Exchange Capacity

In 2018, the University of Bern completed research to characterize external surface area (BET) and cation exchange capacity (CEC) in sedimentary rock cores from the Bruce Nuclear site. Samples from the Queenston, Georgian Bay, Blue Mountain and Collingwood Member formations were evaluated (rock types included claystone, marl and limestone). The research focused on addressing the question of mineralogical fractionation induced by sieving to different grain sizes (i.e., can a specific fraction for geochemical experiments be used and the results considered representative of the whole rock?), as well as the effect of crushing on determined CEC values (e.g., does crushing create new mineral surfaces, and is it permissible to extrapolate geochemical data obtained on disintegrated or crushed material to the intact rock?). The main findings of this work were compiled into a Technical Report for the NWMO in 2019. A modified version of the final report is anticipated to published by the NWMO in 2024.

5.1.5 Geomechanical Properties

5.1.5.1 In-Situ Stress

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

During 2023 further progress was made on developing and applying segmented Bayesian linear regression of in situ stress, and in parallel development began on elicitation of priors for earlier developed Bayesian hierarchical MV linear regression model for in situ stress. An alternative computation method known as importance sampling is being investigated currently together with a prior elicitation approach that can incorporate geological and geotechnical knowledge of a project site. Several analyses of extensive overcoring stress measurements from the SKB Forsmark site in Sweden were performed and presented to NWMO and SKB as part of this research project’s quarterly progress review meetings.

Two conference contributions on segmented Bayesian linear regression of in situ stress listed below were prepared during 2023, whereas the first of these conference contributions received the Best Paper Award in Rock Mechanics or Rock Engineering by the Canadian Rock Mechanics Association (CARMA) at the GeoSaskatoon 2023 conference organized by the Canadian Geotechnical Society (CGS). Furthermore, work on a research article on the Bayesian linear regression of multivariate stress for publishing in a suitable journal began in late 2023 and is currently in progress. A presentation that summarizes the research performed during the STRESSBAY project was delivered by the principal investigator of this research project, Prof. John Harrison, at the NWMO Annual Geoscience Seminar in June 2023.

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 on rock joints at the small scale, 35 × 60 mm, were completed. Twenty-four specimens were tested, where half of them had a natural rock joint and other half had a tensile induced rock joint. Half of the specimens were tested under constant normal stiffness condition (CNS) and the other half were tested under constant normal load condition (CNL). Besides the conventional displacement measurements using LVDTs (which measures the relative displacement between the upper and lower shear box), direct measurements of the relative displacement of the rock joints for all specimens were done using an optical system and analyzed by digital Image Correlation (DIC). Acoustic emission measurements were not carried out in this test series. These were the last set of planned mechanical experiments in the project which makes the data complete for the rock joints at the three scales, 35 × 60 mm, 70 × 100 mm and 300 × 500 mm.

The data from the mechanical experiments on the large-scale fractures (300 × 500 mm) with natural and a tensile induced rock joint were partly analyzed. Results from the normal loading tests (four loading cycles, 0.5-12 MPa) on two natural fractures, denoted by CNL and CNS, are shown in Figure 5-4 as an example. The joint stiffness at the fourth loading (K_N), computed as the secant between 0.5 and 12 MPa, is in the range 150–370 MPa/mm based on local DIC measurements and 37–41 MPa/mm based on indirect LVDT measurements.

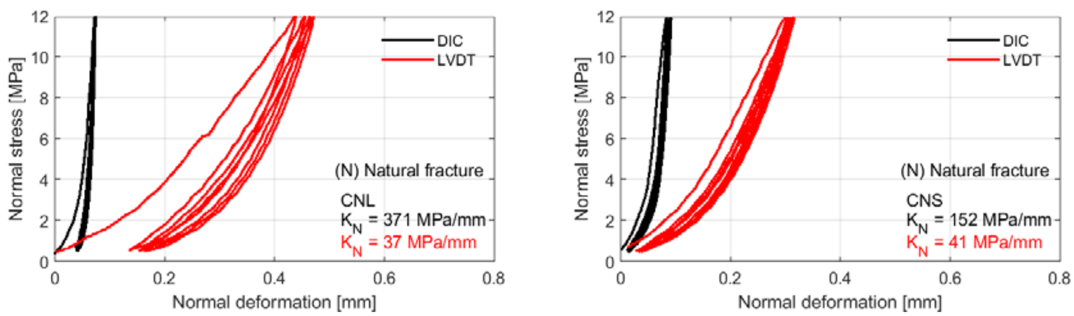


Figure 5-4: POST Project: Normal stress vs. normal deformation and fracture stiffnesses.

Direct shear tests were conducted after the normal loading experiments with a normal stress σ_N = 5 MPa + $K_{N,RM}\cdot\ \delta_N$, where δ_N is the joint dilatancy (mm) and the equivalent rock mass stiffness $K_{N,RM}$ = 0 MPa/mm at CNL and $K_{N,RM}$ = 10 MPa/mm at CNS. The results from two tests are shown in Figure 5-5 The detailed information of the joint displacement obtained by the local displacement measurements (DIC) before fully mobilized shear slip in the joint are novel research data and illustrate the importance of a correct measurement technique. The onset of shear slip, i.e. shear displacement that generates dilation, is around 0.1 mm, whereas the conventional measurements yield a much higher value around 0.3 mm. The elastic, pre-peak, secant stiffness is defined as the values between 0.5 and 5 MPa was ca. 12 MPa/mm based on LVDTs and 40–70 MPa/mm for local measurements by DIC. These results were presented at the ISRM 2023 Congress in Salzburg, Austria (Jacobsson et al. 2023).

The work on evaluating contact pressure distribution measurements and data from fracture geometry scanning is ongoing. This part is mainly conducted within the associated PhD-project about scale effects, with partial funding from Swedish rock engineering research foundation (BeFo).

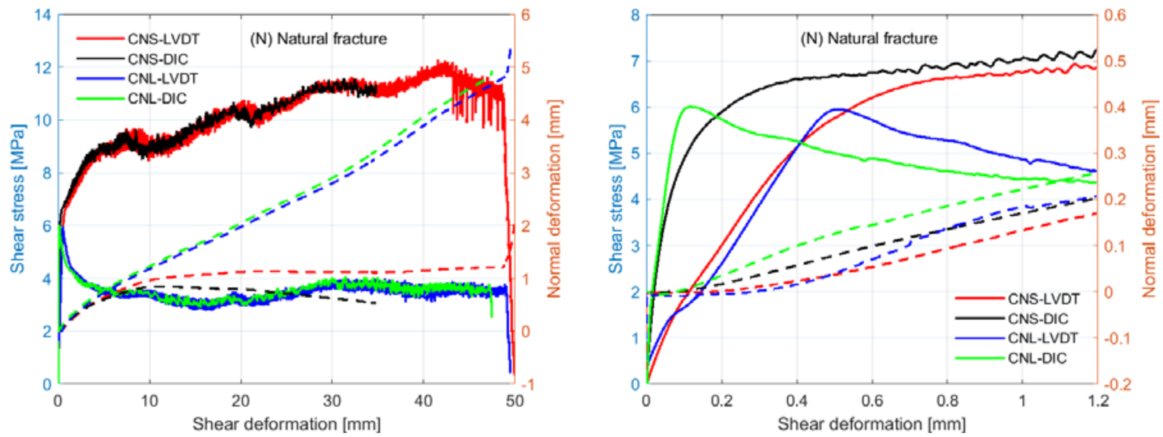


Figure 5-5: POST Project: Shear stress and normal displacement (dilatancy) vs. shear displacement for CNS and CNL specimens. Left: Full scale; Right Close up at pre-peak region. Note that the diagrams have different scales.

5.1.5.3.2 Mont Terri FE-M Project

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

Field measurements are on-going include temperature, pore-water pressure, humidity/water content and suction, thermal conductivity, deformations, and stresses. The program is currently focused on the long-term monitoring of the THM processes confirming the technical readiness of the conceptual modelling framework pertinent to assessment of the long-term performance in the near field scale. Nagra has established a THM modelling task force consisting of Technical University of Catalonia (UPC), the École Polytechnique Fédérale de Lausanne (EPFL), and BGR/TUBAF/UFZ. In 2023, modelling activities continued, which comprises code and calculation verification of TH and THM model results amongst the three teams which used Code_Bright, Code_Aster and OpenGeoSys, respectively.

5.1.5.3.3 Shear Induced Pore Pressure Around Underground Excavations

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

Previous field tests completed at Mont Terri Underground Rock Laboratory (Mont Terri) established that deformations around underground openings in Opalinus Clay are highly dependent on the direction of the excavation relative to the materials bedding. Excavations completed in a direction parallel to the materials bedding have shown higher pore pressures, yielding at relatively small strains compared to laboratory results, and larger than predicted deformations. This research program examines these findings through both a field and laboratory component. The field portion examines two mine-by experiments completed at Mont Terri, one parallel and one perpendicular to the materials bedding, where instruments were strategically placed in front of and around the tunnel's excavation zone. The findings from these experiments will then be compared to the results of a novel laboratory testing program which utilizes micro-fiber optic pore pressure sensors (MFOPs) inside of clay specimens to measure local pore pressures along the shear zone. To recreate the in-situ conditions around the mine-by experiments, a novel servo-controlled direct shear apparatus was developed that is able to apply a strain-controlled (zero dilation) boundary condition with the MFOPs placed inside of the shear zone.

During 2023, research advances for laboratory work included 1) completing a triaxial testing program to demonstrate the functionality of MFOPs inside of overconsolidated clay specimens (Figure 5-6), the results of which were presented at GeoSaskatoon 2023 and are currently under review to be submitted to the American Society for Testing and Materials Geotechnical Testing Journal; 2) modeling of fully-coupled laboratory experiments using FLAC3D to compare against testing results; and 3) the construction and commissioning of the direct shear apparatus as shown on Figure 5-7 with testing scheduled for early 2024. Advances for the field component included 1) the analysis of 3D anisotropic-elastic ubiquitous joint models of the mine-by experiments using the program FLAC3D where the in-situ pore pressure measurements were compared against the model's stress analysis; and 2) the analysis of the mine-by experiments based on the mobilized shear strength as it relates to the pore pressure response and yield surface of the Opalinus Clay. Journal papers for each of the field component results are currently being developed and are planned to be submitted to journals in 2024.

a)

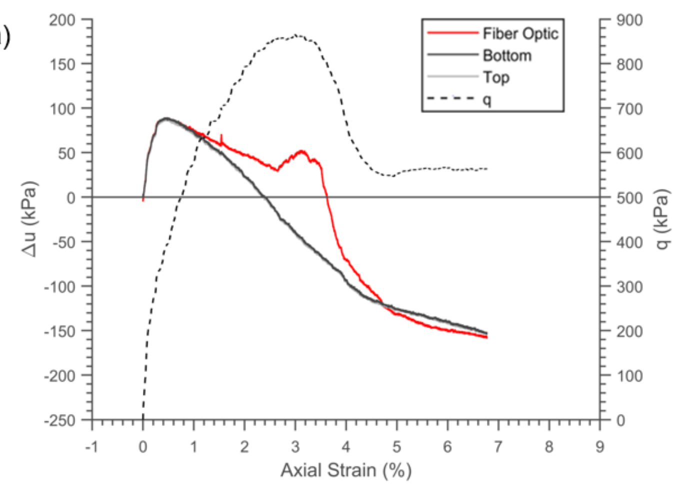


Figure 5-6:: Consolidated undrained triaxial testing results. Example pore pressure response of an overconsolidated kaolinite specimen sheared at the recommended ASTM rate based on the time to 50% consolidation.

Figure 5-7: The developed direct shear apparatus

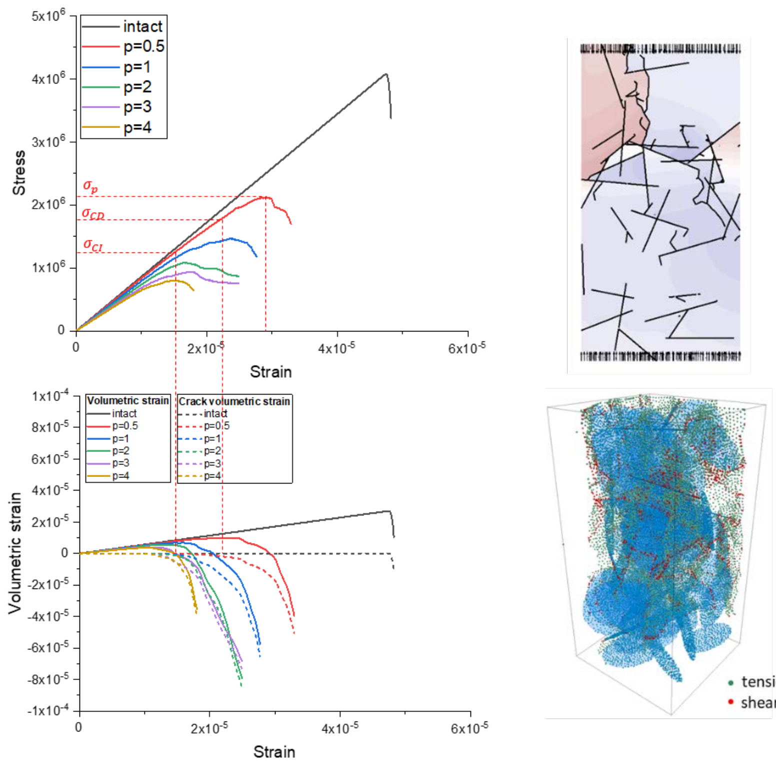
5.1.5.4 Numerical Modelling of Geomechanics

5.1.5.4.1 Rock Mass Effective Properties

This study aims at quantifying the rock mass effective mechanical properties from a DFN approach. The present phase of the project started in 2020 and continued until the Fall 2023. A new phase has started since then.

During 2023, more simulations and analyses have been conducted to investigate the link between the properties of a DFN, initially embedded in a rock matrix otherwise intact (Synthetic Rock Mass specimen), and the resulting rock mass strength for both tensile and compressive conditions. During a loading test, specimen scale properties (e.g. stress, volumetric strain or axial strain) are systematically recorded (Figure 5-8a) together with local failure and increasing damage (Figure 5-8b). One can see that, for UCS conditions, both peak stress and peak strain decrease when increasing the DFN percolation parameter (Figure 5-8a). As for real rock samples under UCS conditions, the stress-strain curves of the SRM samples can be divided into three parts following the analysis of total and crack volumetric strain (Martin and Chandler, 1994). The elastic part corresponds to the linear part of the stress-strain curve until crack initiation stress (σ_{CI}). This corresponds to the point where contacts around pre-existing fracture planes start to break. A crack damage threshold (σ_{CD}) is defined as the applied stress when total volumetric strain reaches a maximum, which may correspond to the point where fracture planes start to connect, speeding up damage evolution. The strain increment needed between σ_{CI} and the peak stress σ_p is much larger for compressive conditions compared to tensile conditions. This emphasizes that more damage around the fractures is needed to reach macroscopic failure. This can also be noticed visually on Figure 5-8b, showing all the damage (broken subcontacts in the numerical model) at peak stress. It is also visible that damage around preexisting fractures occurs both in tensile and shear conditions (green and red dots, respectively in the figure). A total of 120 SRM specimen are defined, based on 20 different DFN model recipes (combination of 5 densities and 4 different fracture size distribution), from which 6 DFN realizations are systematically derived. For each SRM, numerical tests under tensile and UCS conditions are performed. The relationship between the SRM-DFN initial properties and resulting elastic and strength effective properties are analyzed. A journal paper is currently in preparation and a submission is planned in the first half of 2024.

In parallel, we have prepared a paper on the stress fluctuations analyses task of the project. The paper was published in December 2023. With this work we have established the relationship between the stress dispersion coefficients (Gao and Harrison 2016, 2018a, b) and the DFN parameters.



a) b)

Figure 5-8:: Results from numerical simulations of UCS tests. Several Synthetic Rock Mass (SRM) specimens are tested, with embedded DFN of constant fracture size ($2m$) and increasing fracture density (percolation parameter p from 0.5 to 4). a) Stress (top) and volumetric strain (bottom) vs strain curves. Crack Initiation stress (σ_{CI}), crack damage threshold (σ_{CD}) and peak stress (σ_p) are highlighted for the DFN with $p = 0.5$. b) View of the SRM-DFN specimen with $p = 4$. (top) 2D vertical cut view with fractures and local damage traces and (bottom) 3D view of damage (red and green dots) around preexisting DFN (blue dots) (bottom).

5.1.5.4.2 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.
During 2023, time was spent preparing a journal paper "Coupling stress and transmissivity to define equivalent directional hydraulic conductivity of fractured rocks", which is scheduled for submission in the first quarter of 2024.

5.1.5.4.3 Determination of Biot and Skempton Hydromechanical Coefficients for Fractured Rock Masses (BIKE)

This study aims at defining equivalent Biot and Skempton coefficients for fractured rock masses, following a Discrete Fracture Network (DFN) approach to describe the rock mass.

The project began at the end of 2021 with a bibliographic review to support the formalization of the coupled Hydro-Mechanical (HM) behavior at the single fracture scale. The outcome of this task was to propose a way to estimate Biot's and Skempton's coefficients for a single fracture.

In 2022, the methodology was built-up to estimate the Biot and Skempton coefficients at the fractured rock mass scale. The proposed formal expressions for the equivalent Biot and Skempton coefficients, $\overline{\alpha}$ and $\overline{B}$, are given in the equation below. The rock mass is seen as the assembly of a rock into which discrete fractures are embedded, the rock and the fractures being the components of the rock mass, both linearly elastic. Acknowledging the assumption of no interaction, each component deforms according with its own mechanical properties, leading to the following expression:

$$\overline{\alpha} = \frac{\gamma^r \alpha^r + \sum_f \gamma^f \alpha^f}{\gamma^r + \sum_f \theta^f \gamma^f} \quad ; \qquad \overline{B} = \frac{\gamma^r \alpha^r B^r + \sum_f \theta^f \gamma^f \alpha^f B^f}{\gamma^r \alpha^r + \sum_f \gamma^f \alpha^f}$$

Where α^f and B^f are each fracture f Biot's and Skempton's coefficient, respectively; θ_f is the ratio is defined for each fracture as the ratio between the component of the applied stress that act normal to the fracture and the average applied stress; α^r is the rock Biot's coefficient, B^r is the rock Skempton's coefficient; and γ^i is the contribution of each component i (fracture f or rock r) to the total rock mass volume variation.

The validity of the proposed analytical expression was validated against estimations from numerical HM simulations performed in 3DEC7. During 2023, a journal paper based on this work was published (De Simone et al 2023).

5.1.5.5 NSERC Energi Simulation Industrial Research Chair Program in Reservoir Geomechanics

In 2019 NWMO joined the renewal of a multi-sponsor NSERC/Energi Simulation Industrial Research Chair (IRC) and Collaborative Research and Development (CRD) grant program in Reservoir Geomechanics at the University of Alberta. This IRC chair aims to advance experimental and numerical methods, as well as field studies, to help mitigate operation risks and to optimize reservoir management as they pertain to the coupled processes in oil and gas reservoirs. Some of the findings are expected to be also applicable to sedimentary and crystalline rock settings for the geological disposal of used nuclear fuel.

Overall, participation in this multi-faceted IRC-CRD program is expected to advance our understanding of how intact rock and fractures at various scales respond to thermal-hydro-mechanical processes associated with a DGR. The annual research symposium was held during November 01-02, 2023. These symposiums provided sponsors with progress updates on all key research areas underway as part of the program.

5.2 LONG-TERM GEOSPHERE STABILITY

5.2.1 Long-Term Climate Change Glaciation

5.2.1.1 Surface Boundary Conditions

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

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

During 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).

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 is 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 Ignace and South Bruce sites. The depths currently being examined for a deep geological repository at Ignace are 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 will be 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 will be 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, will 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 involved in NWMO’s site selection process, i.e. Ignace and South Bruce. Elements of the work plan include:

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 includes 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 recently submitted to JGR Tectonics.

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 (Norris et al, *submitted a and accepted*) and a revised version is expected to be accepted in 2024. A second, more comprehensive manuscript for submission to *Earth Science Reviews* will be competed in early 2024 (Norris et al., *submitted b*).

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

- Testing of the muogenic nuclide *paleotopometry method.*
- Testing of the muogenic nuclide *paleotopometry method* on the Canadian shield.
- Relative erosion efficacy under different ice sheet velocities.
- 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 2024.

5.2.1.4 Final Borehole Sampling for Greenland Analogue Project (GAP)

Greenland Analogue Project (GAP) is a collaborative research project conducted by SKB, Posiva and NWMO between 2008 and 2013. The primary objectives of the original GAP were to enhance scientific understanding of glacial processes and their influence on both surface and subsurface environments relevant to the performance of DGRs for used nuclear fuel in crystalline shield rock settings.

However, the SKB is planning to terminate the field monitoring and maintenance in Greenland and hand over the GAP boreholes to Danish Technical University (DTU) in 2022. Before the termination and handover to DTU, NWMO jointly with SKB supported the final borehole sampling campaign which involves the withdrawal of high-quality water samples from one of the deep boreholes drilled during the GAP to study how groundwater flow and chemistry at depths equivalent to repository depth. In 2023, lab analysis work for all water samples was completed. Efforts are underway to publish the collected data. In 2023, lab analysis work for all water samples was completed. Efforts are underway to publish the collected data. Figure 5-9 is a photo taken in 2022 at the sampling borehole during the water sampling campaign in Greenland.

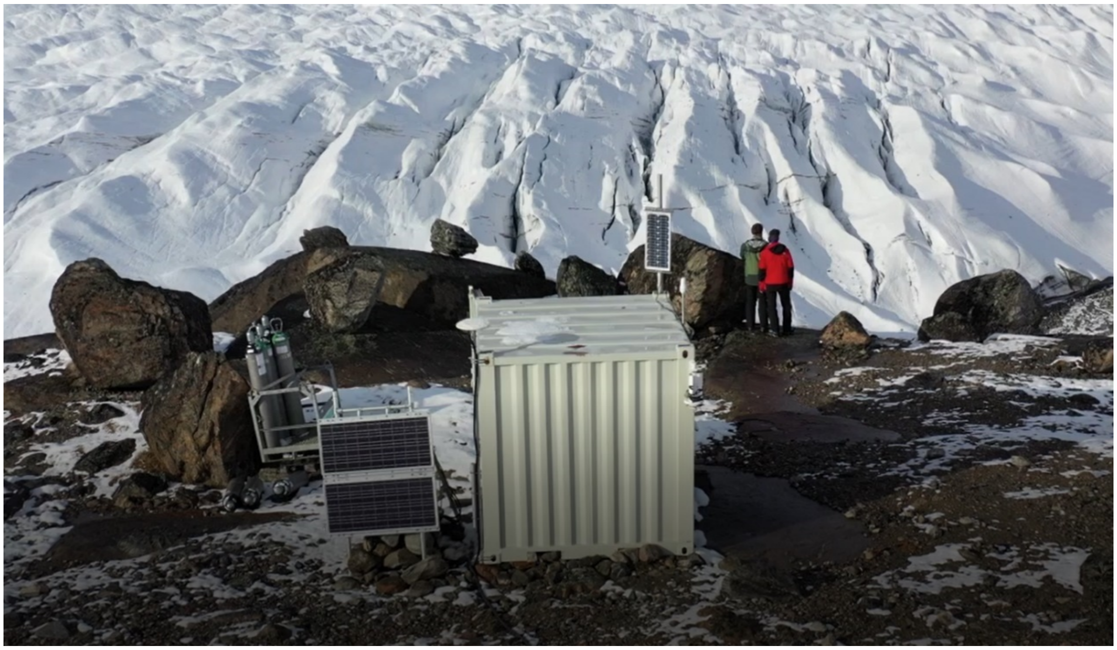


Figure 5-9: The Well-head Container of Borehole DH-GAP04 (Photo by Lillemor Claesson Liljedahl)

5.2.1.5 Glacial and Proglacial Environment – Numerical Modelling

5.2.1.5.1 CatchNet Project

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

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

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

5.2.1.5.2 McGill University

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 2023, the PhD program was on-going.

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.

5.2.1.5.3 University of Laval

In 2022, a PhD program supported by NWMO was initiated at the University of Laval. The research program will be focused on numerical modelling of permafrost-impacted groundwater flow systems, aiming to deepen our understanding of the effect of permafrost growth and decay cycles on the thermal regime and groundwater flow field within the near and far-field environment of a DGR. This program will take advantage of the long-term field data collected from two well-characterized permafrost sites maintained by the University of Laval: Salluit (continuous) and Umiujaq (discontinuous). See Figure 5-10 for locations and permafrost conditions of these two field sites.

In 2023, a 2D modelling of hypothetical geosphere setting in the Canadian Shield was employed to assess the impact of permafrost growth and decay cycles on groundwater flow and thermal conditions. Initial simulation results show that permafrost cycles can potentially 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.

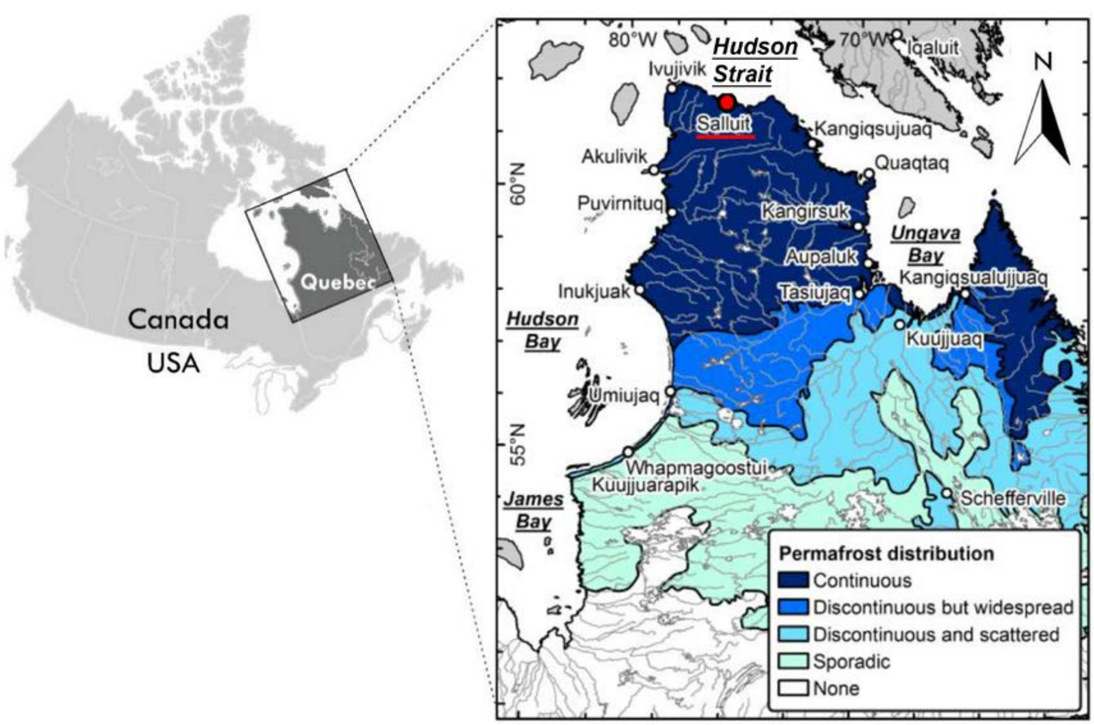


Figure 5-10: Location of Existing Research Sites at Salluit and Umiujaq, Nunavik, Québec (after Lemieux et al. 2020)

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. 2022a; Su et al. 2021; Su et al. 2020). A 3D demonstration simulation based on a hypothetical sedimentary basin has been performed to evaluate the code capabilities for large-scale flow and reactive transport simulations using unstructured meshes. The new code capabilities allowed to evaluate the effect of dimensionality (2D versus 3D) and ice sheet geometry on the development of flow patterns and solute transport in sedimentary basins during a glaciation cycle. The numerical experiments indicate that a 3D analysis will give more comprehensive results for flow patterns and reactive solute transport subjected to glaciation/deglaciation cycles in the case of a narrow ice lobe, but also suggest that a 2D approach might provide an adequate representation for the case of a relatively wide ice sheet (Su et al. 2022b).

The impact of paleo-glaciation on the formation and distribution of elevated dissolved sulfide is also being investigated through reactive transport simulations. MIN3P-THCm was previously applied to investigate the mechanisms responsible for elevated dissolved sulfide observed in the Michigan Basin (Xie et al. 2018). These simulations have recently been updated using a more detailed realization of the geochemical network including ferrous and ferric iron and associated redox and mineral dissolution/precipitation reactions. Simulation results show improved agreement with the available field data (Xie et al. 2023).

A two-year new work program initiated in 2023, in collaboration with University of British Columbia and University of New Brunswick, to perform (1) the reactive transport modelling of noble gases in sedimentary and crystalline rocks; (2) reactive transport modelling of reactive transport in fractured media; (3) sedimentary basin reactive transport modelling based on South Bruce and/or Bruce Nuclear Site data; (4) literature review on iodine mobility in porous and fractured media; and (5) a literature review of other international programs to identify research gaps in reactive transport modelling.

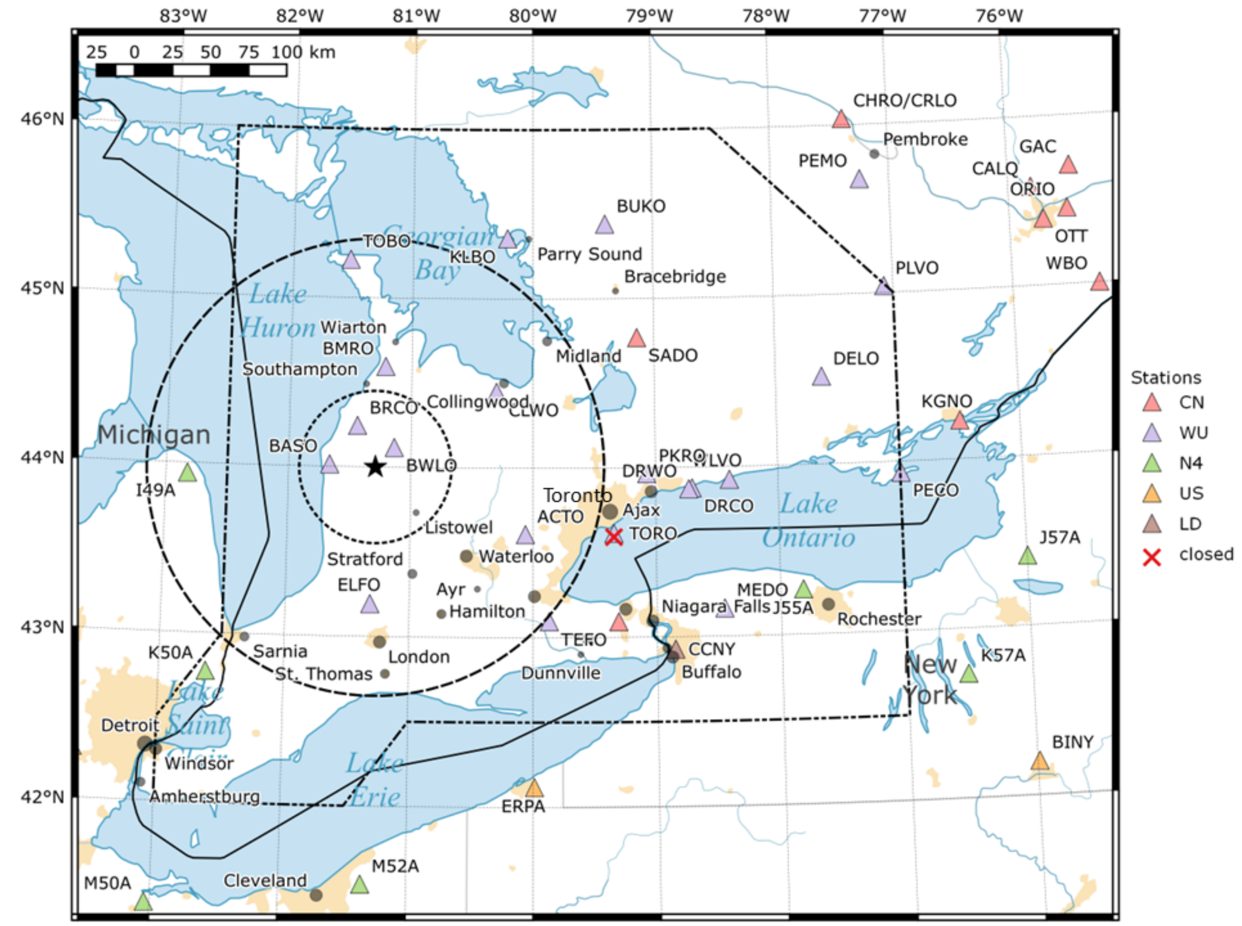
In 2023, progress towards this new work program has been made by developing a general formulation for the ingrowth of noble gas isotopes (He, Ne, Ar, Kr and Xe) and implementing it in MIN3P-THCm. The new extension was applied to simulate noble gas ingrowth in the Michigan Basin, demonstrating its suitability to investigate natural ingrowth of ^{4}He and ^{40}Ar in sedimentary rocks. In addition, a pre-existing formulation for partitioning of entrapped gases between the aqueous and gas phases was extended for noble gases and tested to investigate the partitioning behavior of the various noble gases in the presence of a gas phase. In addition, reactive transport modelling capabilities for fractured media have been implemented in MIN3P-

THCm. The utility of anisotropic quadrilateral mesh discretization has been investigated for improving the efficiency of reactive transport modelling in porous media with fracture networks. An improved cell-based Green-Gauss gradient reconstruction method has been implemented to improve numerical stability, especially for discretizations with large aspect ratios.

5.2.3 Seismicity

5.2.3.1 Regional Seismic Monitoring

The Canadian Hazards Information Service (CHIS), a part of the Geological Survey of Canada (GSC), continues to conduct a seismic monitoring program in the northern Ontario and eastern Manitoba portions of the Canadian Shield. This program has been ongoing since 1982 and is currently supported by a number of organizations, including the NWMO. CHIS now provide monitoring of both northern Ontario and southern Ontario.



Notes: The SON-South Bruce area is indicated with a black star, and dashed circles are approximately 50 and 150 km radii around this site. The black polygonal (dash-dot-dotted) outline is the area used for recurrence calculations (see Section 5.2). Triangles are operational stations, coloured by network code. Stations that closed during 2021-2022 are marked with an X.

Figure 5-11: Seismograph Stations in Southern Ontario, 2019–2022.

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 2021–2022, four earthquakes occurred within 150 km of the SON-South Bruce area (Figure 5-11), all less than m_N 2. The low rate of events in the study area for those two years is consistent with historical findings of few earthquakes, and the assessment of this area as representing a low seismic hazard region stands.

With the refocusing of the study area to the SON-South Bruce area, the earthquakes of interest have changed slightly. Since 1950, just one earthquake has been located within 50 km of the SON-South Bruce area. This was a magnitude 3.0 m_N event recorded in 1952 at only three stations. At the time that the event was catalogued, it was considered unusual that the event was not reported as felt, but local newspapers were never checked. It is recommended that the possibility of carrying out such a search today be investigated. Another consequence of the refocusing of the area of study is that the Bruce Nuclear sub-network is not ideally suited for monitoring micro-seismicity near the SON-South Bruce area. To this end the NWMO has commissioned a new microseismic monitoring network.

5.2.3.2 Mont Terri Nanoseismic Monitoring (SM-C) Experiment

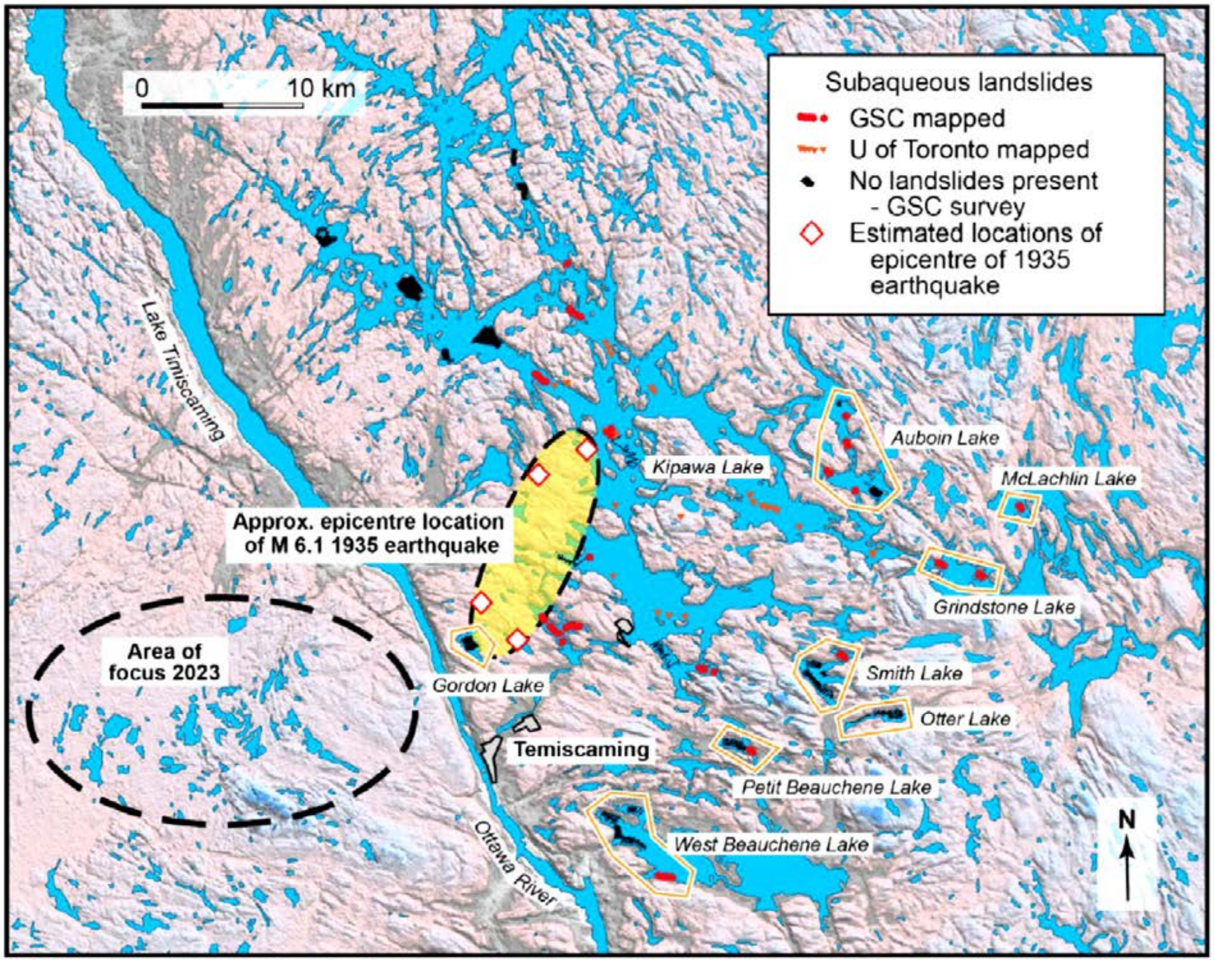
The NWMO is involved in the Mont Terri Nanoseismic Monitoring (SM-C) Experiment, which serves as a comparative tool for the NWMO microseismic monitoring program. During 2023, upgrades were finished and all tiltmeters have now been digitized.

These 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 are ongoing through 2023. The results of previous injection experiments are published in Guglielmi et al. 2021 and Zapone et al. 2020.

5.2.3.3 Paleoseismicity

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

During 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, 2023 (Figure 5-12). For 2024 an open file report concerning the 1935 Temiskaming earthquake will be published in Q2. This will be followed in July with a second open file report, which will focus on the sub bottom profiling of Lake Temiskaming and the methods employed for the study.



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 5-12: 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 Queen's Geomechanics and Geohazards Group, QGGG, has continued its development of predictive tools for Excavation Damage Zone (EDZ) evolution around deep geological repositories in sedimentary and crystalline rock, focusing on robust and universally applicable EDZ damage threshold definition and updated conventional testing and investigation tools. This improvement of laboratory testing methods is coupled with the development of advanced numerical approaches for prediction of EDZ as well as quantifying the evolution and impact of damage (fracture density, propagation, aperture, and connectivity). The following is a summary of the developments in 2023.

Recently completed work has proven the value of a practical and inexpensive upgrade to the standard indirect Brazilian tensile strength (BTS) laboratory procedures (Packulak et al 2024). While this technique is not mentioned in the available testing standards and guidelines, using a single strain gauge to detect the onset of cracking allows the true tensile strength (TTS) to be easily determined. Other long-standing issues such as the influence of BTS platen alignment (high sensitivity of platen alignment even within the tolerances specified in testing standards) have been resolved (Packulak and Day 2022) and the impact of anisotropy on BTS results (Packulak et al 2023a and b) have been extensively studied and solutions have been developed.

The use of Digital Image Correlation (DIC) has been extensively optimized in 2D for the BTS test configuration (Gagnon et al 2023, Packulak et al 2023b, Woodland et al 2023). Due to the small strains involved in BTS tests on low porosity rocks, numerous sensitivities and inherent inaccuracies plague this method. Most of the challenges of adopting this method for rock mechanics have been resolved through this work. The work is being extended to 3D monitoring of unconfined compressive strength (UCS) tests, specifically for heterogenous and anisotropic rocks. The method gives a fully circumferential strain map of the entire test and is being compared to previous QGGG innovations in fiber optic strain measurement of cylindrical laboratory tests. Both techniques are proving valuable in whole sample strain measurement and mapping for damage analysis.

Strain-based determination of brittle damage thresholds in low porosity rocks has been extensively studied. Inherent non-linear elastic behaviour has been identified in many granitic, gneissic and sedimentary rock samples, complicating the existing damage detection procedures. Extensive testing and analysis have been carried out to create a more robust and geologically independent damage monitoring approach.

The use of Acoustic Emissions (AE) to understand damage processes is the subject of both past and current studies. Full waveform analysis is being simplified for general use in testing interpretation, including differentiation between extensile (MODE I) damage and shear (MODE II) damage accumulation. We are also developing procedures to measure and validate the use of AE in BTS tests to detect the TTS and subsequent fracture evolution (Malicki et al 2024). The impact of lithology on the linearity of elastic stress-strain behaviour has been investigated. Young’s modulus and Poisson’s ratio are the most common parameters for geomechanics numerical modelling input but are just engineering constructs. The stress and confinement dependency of elastic parameters in rock may require integration into detailed analyses. Experimental investigation regarding the stiffness tensor of anisotropic rocks (with healed or metamorphic fabric) has recently been completed and has resulted in a validated single sample approach; in contrast, conventional methods rely on multiple samples with different fabric orientations, which is a situation often not practical with exploration drilling campaigns. Companion studies on the impact of loading conditions and confinement on acoustic velocity and the subsequent calculation of dynamic stiffness parameters has yielded valuable insight. Ongoing work to understand the impact of healed structure, including veins of various genetic characteristics, on rock strength and damage evolution has been continued and is being extended to multi-veined systems and different vein genesis categories (Gagnon and day 2023).

The challenge of characterizing the impact of surface anisotropy for clean, rough, or slickensided joint surfaces is the subject of ongoing work (Hoyle et al 2023). Photogrammetry and 3D mold printing (for replicate cast cement samples) allows for shear testing in any direction through 360 degrees to map the influence of anisotropy relative to the based sample. This will add important levels of additional accuracy to 3D jointed simulations.

Modelling of rockmasses with multiple impersistent joints or veins, and the resultant impact on EDZ around tunnels has been studied using pseudo-discontinuum finite element modelling (Fischer and Diederichs 2023), while post yield fracture development has been the subject of research using discrete element modelling. A state-of-science review of direct shear testing of rock fractures with a focus on multi-stage and boundary conditions was done by MacDonald et al., (2023).

6 REPOSITORY SAFETY

The objective of the repository safety program is to evaluate the pre-closure and post-closure safety of the candidate deep geological repository. In the near-term, during site selection, this objective is addressed through preliminary site-based studies, incorporating progressively more site details.

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). The 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).

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.

The projected future total number of used fuel bundles produced by the existing reactor fleet is approximately 5.6 million bundles (107,000 Mg heavy metal), assuming the information published as of December 2023 on Darlington and Bruce reactors refurbishment and life extension plans, as well as continued operation of Pickering A until 2024 and Pickering B until the end of 2026. If Pickering B extended commercial operation, including potential refurbishment plans were assumed, the total number of used fuel bundles would be approximately 6.0 million bundles (116,000 Mg heavy metal) (Reilly 2023).

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

The Canadian used fuel inventory and forecast are updated annually by the NWMO with the most recent fuel inventory and forecast documented in Reilly (2023).

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, 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)).

The legacy metallic U and U carbide fuels from the early stage of fuel development will likely be converted 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 Corrosion of Zircaloy Cladding

Zirconium alloys are widely used in nuclear reactors as fuel cladding and are, therefore, a component of the waste materials that will be emplaced in a deep geologic repository. In 2023, a review and update of the previous study on the corrosion of Zircaloy (Shoesmith and Zagidulin 2010) was performed (Zagidulin and Shoesmith 2023). The update focused on the corrosion/degradation behaviour of fuel cladding during interim storage at the reactor sites and DGR conditions. Since most of the known degradation mechanisms are inactive, no significant degradation will occur during interim storage.

Zirconium and titanium are highly corrosion resistant light metals that exhibit many similarities and passivate by the formation of extremely insoluble M^{IV} oxides. Since the data base for the corrosion of titanium alloys under general industrial and repository conditions is extensive, the electrochemical and corrosion behaviour of the two materials has been compared and evaluated.

Exposure of the fuel cladding to the groundwater in a DGR will only occur if a Used Fuel Container fails. While electrochemical studies suggest Zircaloy cladding could be susceptible to localized corrosion in the form of pitting, redox conditions inside a failed container, established by the gamma radiolysis of groundwater, will be insufficiently oxidizing to support this process. This leaves general passive corrosion under anoxic conditions, which could lead to hydriding due to the absorption of hydrogen into the cladding, as the only significant degradation process. The available data shows that, even if the thick oxide on the cladding on discharge from reactor is ignored, the corrosion rate will be very low and conservatively within the range 1 to 5 nm/a (Zagidulin and Shoesmith 2023). While the possibility that the final failure process will be due to hydriding cannot be ruled out, times to failure should be in the region of 10^5 years or longer.

6.2.3 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 2023, 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). Phase VI of the NEA Thermodynamic Database (TDB) project will provide a review of the chemical thermodynamics of lanthanides. The review of the chemical thermodynamics of selected ancillary compounds of interest to radioactive waste management has been completed and will be published in 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.

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

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; (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 2021); 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 results of the research on thermodynamic properties of uranyl chloride complexes have been re-evaluated and refitted to be incorporated into the PHREEQC database. The uranyl chloride work, including the PHREEQC compatible parameters will be published as an MSc thesis and in a journal article in 2024.

The NWMO updated the databases of radionuclide solubility for Canadian crystalline rock environment (Colàs et al. 2021) and Canadian sedimentary environment (Colàs et al. 2022). The radionuclide solubility limits were calculated in a reference groundwater CR-10 (Ca-Na-Cl type with TDS = 11 g/L) which simulates the groundwater geochemical conditions at the repository depth of Canadian crystalline rock, and in a reference groundwater SR-290-PW (Na-Ca-Cl type with TDS = 287 g/L) which simulates the groundwater geochemical conditions at the repository depth of Canadian sedimentary rocks. The solubility calculation in SR-290-PW was carried out using a Pitzer database DGR_Pitzer_TDB which has been developed based on the Yucca Mountain Pitzer database data0.ypf.R2 (Jove-Colon et al. 2007) and modified with additional information from the THEREDA database (Altmaier et al. 2011) and the available Pitzer data from the literature.

In 2023, the DGR_Pitzer_TDB database was further evaluated/developed to increase its accuracy, applicability and transparency, including: 1) comparison of the relevant thermodynamic data for the Na-K-Ca-Mg-CO_3 system in DGR_Pitzer_TDB with that in THEREDA (Altmaier et al. 2011); 2) review of the relevant thermodynamic data selection for those elements of interest whose chemistry is significantly affected by chloride complexation (Ag, Bi, Cd Cu, Pb and Pd); 3) evaluation of the thermodynamic data of $An(CO_3)_5^{6-}$ complexes (An= U(IV), Np(IV) and Pu(IV)); 4) evaluation of thermodynamic data for radionuclides Th, Np, Pu and Am; and 5) analysis and enhancement of the thermodynamic data for the Ca-(Mg)-CO_3 system at 25°C.

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 2023, the NWMO continued to participate in this forum and to sponsor the Transport of C-14 in the Biosphere project, initiated in 2021. The primary objective of the project was to investigate the use of new conceptual models for the transport of C-14 releases from geological disposal facilities for solid radioactive wastes. The scope of the project included literature review, conceptual models, and preliminary mathematical models for terrestrial, freshwater, and marine environments. The final BIOPROTA report was published by SKB in 2023 (Thorne et al. 2023).

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 2023, the NWMO developed a broad set of human receptors to be used in pre-closure safety assessments. The receptors are defined by a range of lifestyles and include a theoretical receptor assumed to maximise the potential exposure (Most Exposed Group) and several illustrative local lifestyles. As engagement with local communities increases, the illustrative local lifestyles will be updated to better reflect public interests.

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 2023, 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 public dose analysis was carried out in 2023 for both the Revell Site and South Bruce Site, to estimate the potential radiological impact to the public from normal operation of the DGR and its related surface processing facilities. A conceptual design of the DGR with potential site-specific surface facilities layouts were considered for these studies. 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 receptors at a several locations, including a potential fence line location and locations relevant to the lifestyles of the local communities. The preliminary normal operation analysis indicates that the potential public doses would be below the preliminary acceptance criterion. This preliminary analysis is continuing to incorporate site specific information and will inform the further development of the preliminary DGR design.

6.4.1.3 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-1.1.1 (CNSC 2018) and REGDOC-2.4.4 (CNSC 2022).

In 2023, 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 public dose analysis was carried out in 2023 for both the Revell Site and South Bruce Site, including assessing the potential public dose consequences for several accident scenarios consistent with the identified external and internal hazard assessment noted above. The analysis considers exposure to a person standing at various distances from the fence line under conservative generic atmospheric conditions. Atmospheric dispersion factors were derived based on the Gaussian dispersion model described in CSA N288.2-M91 (CSA 2003). 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.

6.4.1.4 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 2023, additional used fuel configurations were analysed to progress the radiological characterization of the used fuel, including used fuel containers in Transfer Casks, transportation packages, buffer boxes, and in various stages in the underground placement rooms.

6.4.2 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.

6.4.2.1 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. Preliminary acceptance criteria were used in NWMO's generic case studies (NWMO 2017, 2018). In 2023, the NWMO advanced the work on developing the 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.

6.4.2.2 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 2021). The 2023 preliminary work towards site-specific analyses of the Revell Site and South Bruce Site included:

- Updates to the site-specific post-closure analysis consistent with engineering, geoscience and environmental assessment data available at the end of 2022;
- Refinement and further development of conceptual models of the Revell and South Bruce Sites and to the Integrated System Model (see Section 6.4.3.2.1) used to assess repository performance in the post-closure period;
- Refinement to the set of scenarios considered in the post-closure assessment including normal evolution and alternative scenarios (disruptive events, what-if, and human intrusion scenario);
- Consideration of multiple types of water-supply wells at surface and a variety of illustrative human receptors specific to the Revell Site (Boyer and Reilly 2023).

Key uncertainties investigated in the 2023 preliminary post-closure analysis of the Revell Site included studying the effect of:

- Varying fuel dissolution rates on repository performance;
- Depth, rock and fracture transmissivity on repository performance; and
- Repository standoff to layout limiting fractures on repository performance.

Key uncertainties investigated in the 2023 preliminary post-closure analysis of the South Bruce Site included the effect of:

- Varying fuel dissolution rates on repository performance; and
- Glacial erosion on repository performance.

6.4.2.2.1 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 HGS describes the movement of species from the repository via the groundwater through the rock mass and fractures, to the surface environment. The ISM-BIO model developed using AMBER determines the concentration of species in environmental media (e.g., surface water, groundwater, sediments, soils, air) and estimates the consequent radiological dose to a most exposed group and a variety of illustrative receptors living near the repository.

In 2023, the ISM v1.3 was released, which further refined the site-specific nature of the ISM-GEO and ISM-BIO models for the Revell and South Bruce Sites. The theory of the component models of the initial ISM versions was described in Gobien et al. (2022, 2023). Figure 6-1 shows the structure of the ISM component models combined with the data processing and linking tool known as paLINK.

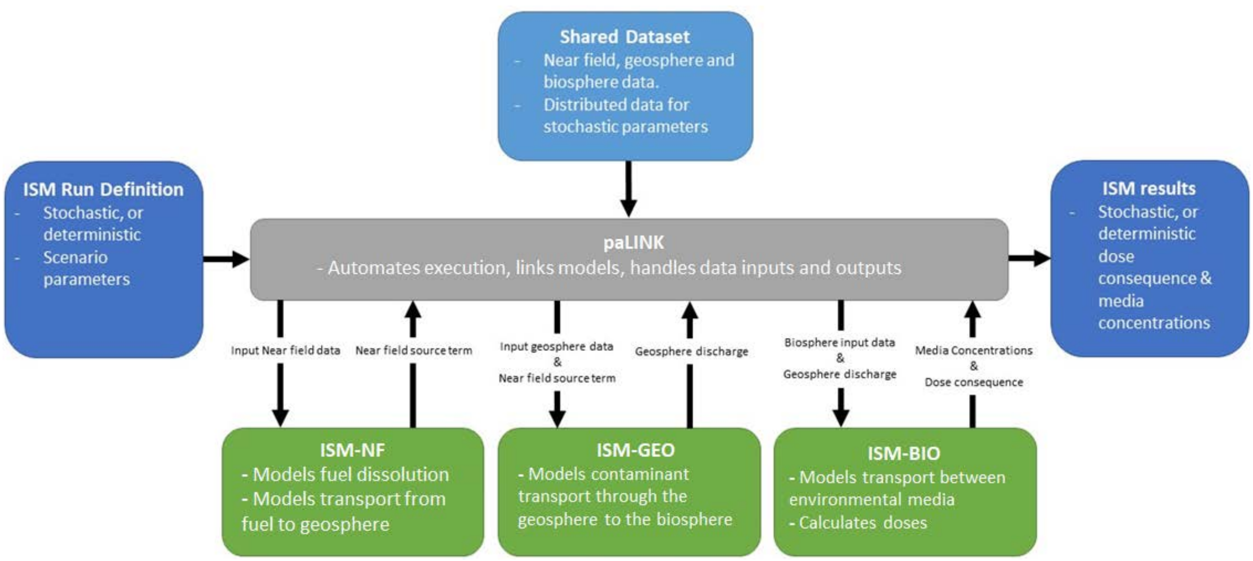


Figure 6-1: paLINK-ISM Configuration

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 2021). The next iteration, ISM v1.4, is planned to consider a wider variety of wasteforms (e.g., prototype and research reactor fuels) and is expected to be released in 2024.

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 4.4.3.2). A preliminary validation report is in development.

6.4.2.3 Dose Rate Analysis

The used fuel container is a major engineered barrier that must be strong enough to withstand geological pressures, including the hydrostatic load of glaciation events, and chemically resistant to long-term corrosion. In the event of the failure of a fuel container, groundwater could enter the container and contact the fuel. Consequently, estimates of alpha, beta, gamma, and neutron dose rates in the water near the fuel container and fuel surfaces are required to support the assessment of the potential effects of the radiolysis of water on the integrity of the container and the used fuel.

The dose rate estimates were updated in 2022 using the latest used fuel inventories (Heckman and Edward 2020), container designs, and state-of-the-art computational method. The dose rate calculations included contributions from alpha, beta, gamma, and neutron sources in the used CANDU fuel. Dose rates were estimated for decay times up to 10 million years, for two burnup values (220 MWh/kgU and 290 MWh/kgU), and for various used CANDU fuel configurations (i.e., single fuel bundle immersed in water, UFC immersed in water, breached and water-filled container, and a placement room). The report was revised in 2023 to include the dose rate profile inside a dry-air filled UFC and inside a humid-air-filled UFC (Ariani 2023).

6.4.2.4 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 2023, an integrated THM model was built to explore the importance of scale in modelling THM response in a sedimentary host 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 7 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).

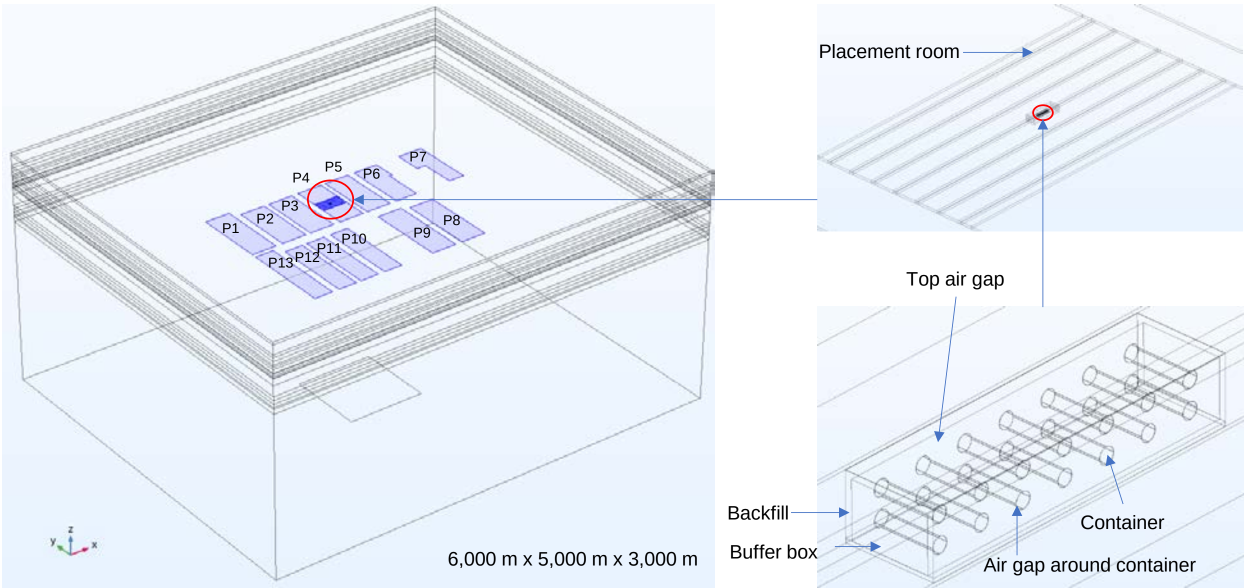


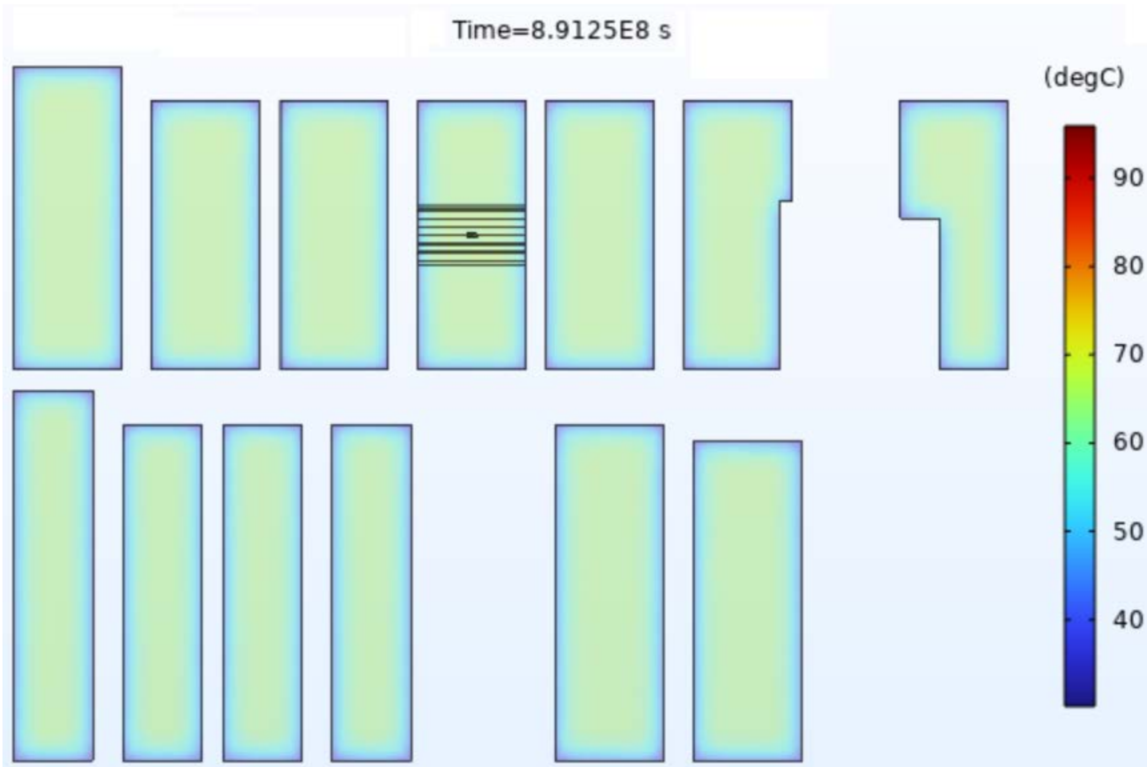
Figure 6-2: THIM Model Geometry

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 96 ºC occurring after about 28 years (Figure 6-3).

This study compared the results from an integrated TM model and from a TM near-field model with the results from this integrated THM model. The comparison showed that the results from the integrated TM model and from the TM near-field model cannot be used to represent the results from the integrated THM model. The influence of the bentonite sealing material saturation on the thermal, hydraulic and mechanical response were also studied.

This study also included several sensitivity studies including:

- Sensitivity to material properties such as host rock and excavation damaged zone thermal conductivity and permeability;
- Sensitivity to mechanical boundary conditions such as those applied to the outside vertical boundary of the model and the bottom of the model.
- Sensitivity to the vertical extent of the model domain on uplifts induced by the DGR; and the influence of glaciation (with and without ground surface erosion).



(a)

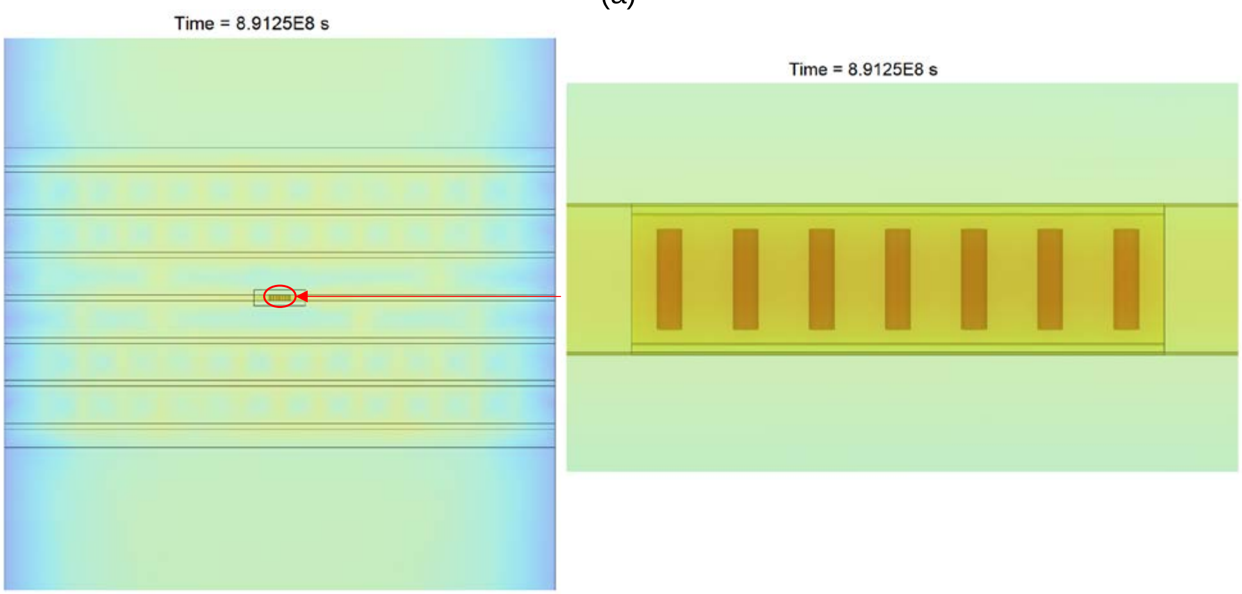


Figure 6-3 : Temperatures in Different Panels (a) and Placement Rooms at Center of Panel 4 (b) after 28 Years of heating from the Coupled THM Integrated Model.

6.5 CONFIDENCE IN SAFETY

In 2023, the Confidence in Safety reports were updated for each site (NWMO 2023c, NWMO 2023d). The purpose of these reports was to summarize the results as of late 2023 indicating why each site would be suitable from a technical perspective for hosting a repository. They are intended to support public discussion around site selection.

The NWMO's assessment of the suitability of the South Bruce Site described in NWMO (2023c), was based on both intrinsic characteristics of the multiple-barrier approach, plus the evidence of the suitability of the rock at the South Bruce Site from recent studies. The key points are:

- The Cobourg Formation is the preferred rock formation, and boreholes confirmed it was at the expected depth of around 650 m at this site.
- The Cobourg Formation is surrounded by 100s of meters of strong rock.
- No inflowing groundwater into boreholes below 325 m.

The NWMO's assessment of the suitability of the Revell Site described in NWMO (2023d), was also based on both intrinsic characteristics of the multiple-barrier approach, plus the evidence of the suitability of the rock at the Revell Site from recent studies. The key points are:

- The Revell Site is in a 2.7-billion-year-old, stable and strong granitic rock.
- It is consistent with other similar Canadian Shield rocks and with the types of rock at the Finland and Sweden repository sites.
- Site specific information indicates that below about 650 m there is a zone with favorable characteristics for hosting the repository.

These reports are part of a multi-year assessment process. In both cases, further work including detailed site characterization is planned, should the site be selected, in order to obtain the information needed for the regulatory licence application. Ongoing and future technical work will include further site studies, design development and safety analyses to confirm and extend the results to date. These would ultimately be presented to Canadian federal regulators for an Impact Assessment and a series of regulatory licence applications. This is a process that will take years before a final approval to construct could be received. During construction and operations, there will be continued monitoring to ensure that the site is, and remains, suitable for long-term containment and isolation of used nuclear fuel.

6.6 MONITORING

6.6.1 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, as well as participated in the EGAR and EGAP organized workshop "*The Medium and the Message: Challenges and Solutions in Selecting and Preserving Records of Radioactive Waste*" in Solna, Sweden in September 2023.

7 SITE ASSESSMENT

In 2023, 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. The status of the geological and environmental studies underway in these regions is described below.

7.1 WABIGOON LAKE OJIBWAY NATION (WLON)-IGNACE AREA

7.1.1 Geological Investigation

By the end of 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 throughout 2023. These latter activities provided support for the integration and synthesis of site-specific information in support of advancing geoscientific site understanding.

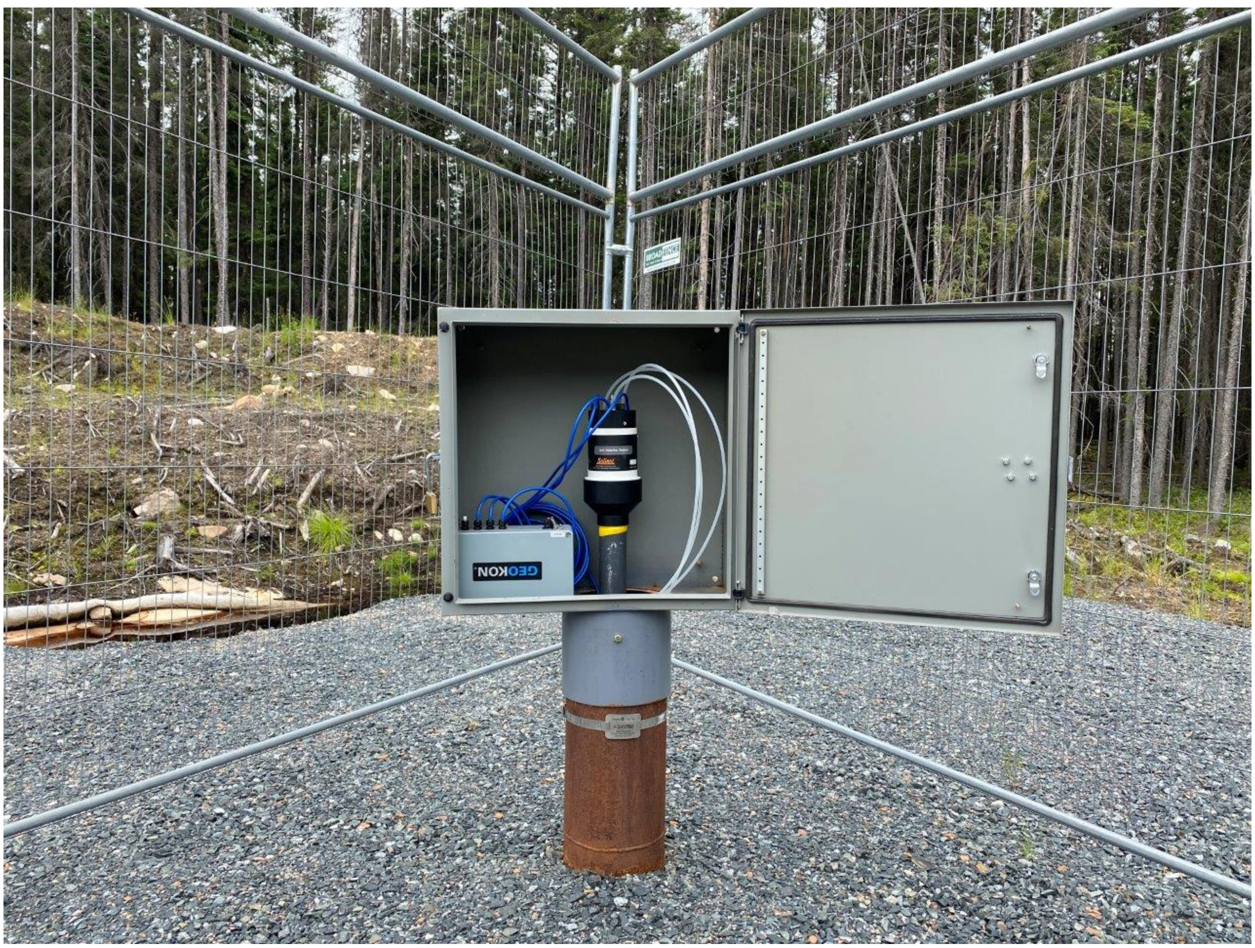


Figure 7-1: Installed shallow groundwater monitoring well in the WLON-Ignace area.

7.1.2 Environmental Program

A key piece of work completed in the Northwest for 2023 included the completion of Year 2 of the environmental media baseline monitoring and the continuation of Tier 1 biodiversity work, including further bat research. Additionally, the Year 1 Environmental Media Baseline Report and Environmental Media Change Assessment Report were both publicly released.

Baseline media and biodiversity work completed in 2023 included: surface water quality monitoring, hydrology, atmospheric studies, aquatic habitat mapping, and Environmental DNA (eDNA) 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 2023 are described below.

7.1.2.1 Surface Water Quality, Hydrology, and Aquatic Habitat Mapping

Surface water quality monitoring was completed in partnership with Wabigoon Lake Ojibway Nation community members. During the winter and spring campaigns a total of 41 sites were visited and 115 samples collected. The surface water monitoring campaign also included sediment and benthic invertebrate sampling at select sites. Hydrology monitoring was completed and included bathymetry and lake level monitoring (Figure 7-2) at 11 lake and pond sites and flow monitoring at 6 stream and river sites. A spring campaign for aquatic habitat mapping was completed during the month of May and included the completion of surveys at a total of 181 sites.

Figure 7-2: Photo Showing Field Crews Measuring Flow with an Acoustic Doppler Current Profiler (ADCP).

7.1.2.2 Atmospheric Monitoring

In 2023, Year 1 of the air quality monitoring portion of the overall atmospheric work was started in the Northwest. Field consultants deployed an atmospheric monitoring trailer (Figure 7-3) to act as the main station during the study period. Sampling at the main station includes continuous, passive, and active sampling methods. A total of two Local Study Area (LSA) dust fall samplers were deployed within the Area of Interest (AOI) in the Fall of 2024. Sampling at the LSA stations is all passive. Field consultants returned monthly to complete sampling at each station and will continue to complete monthly sampling throughout 2024.

Figure 7-3: Photo Showing the Main Site Study Area (SSA) Atmospheric Monitoring Trailer for WLON-Ignace.

7.1.2.3 Environmental DNA

Aquatic eDNA sampling was completed in partnership with Wabigoon Lake Ojibway Nation community members. During the spring campaign field crews visited 10 collection sites and collected a total of 44 aquatic eDNA samples.

The NWMO and the University of Guelph have partnered on a joint environmental DNA (eDNA) research program to further understand biodiversity conditions around the potential repository sites in the Wabigoon Lake Ojibway Nation-Ignace area and the Saugeen Ojibway Nation-South Bruce area. eDNA is a non-invasive technology to detect what species are present 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, 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. The data collected as part of NWMO's eDNA program will be shared with global databases so that future projects can benefit from our learnings.

7.1.2.4 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 2023 included continued passive acoustic monitoring of bats at eight locations on and around the Revell and Ignace area, and eight nights of mist netting surveys to capture bats (Figure 7-4). Capture surveys yielded 24 captured bats of four species across three sites: one big brown bat, sixteen silver-haired bats, six endangered little brown myotis and one hoary bat.

Youth engagement was another factor included in the bat program work in 2023. Youth from Wabigoon Lake Ojibway Nation joined Toronto Zoo Native Bat Conservation program representatives and NWMO staff in the field or a night of mist netting surveys. The youth attending learned how to set up the survey equipment and how bats are captured, observed and data recorded, and then safely released.

Figure 7-4: Photos from an Evening Field Monitoring Session Near in the WLON-Ignace area. The Little Brown Myotis (Left) and the Silver-haired Bat (Right) are Displaying Typical Behaviour when Handled by Opening Their Mouth to Echolocate and Gain an Understanding of What is Going On.

7.1.2.5 Engagement

Engagement related to the environmental program is ongoing in the Northwest. In 2023 this included representation at community events such as open houses and providing information and environmental work updates to various community groups. An environmental day camp was 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 and plants. Day camp participants also took part in the collection of edible and medicinal vegetation found in the area that was submitted for laboratory testing as part of the Northwest Community Sampling Program for tissues.

NWMO environment staff and representatives from KGS Group, North/South Consultants, and Scatliff + Miller + Murray attended the two-day long Northwest Nuclear Exploration Event in the community of Ignace. During the event an environment program booth was set up to showcase the programs being run in the Northwest and to allow visitors to ask NWMO and field staff questions about the work and any results that had been found so far (Figure 7-5). The Manager of the NWMO's Environment Program also presented an update to the community during one of the exploration event workshops.

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

7.1.2.6 Planned 2024 Work

Going forward into 2024 the environmental team aims to continue monitoring and compliance initiatives for work completed in the Northwest, continue working with community members as part of the baseline monitoring program and continue executing the Environmental Baseline Monitoring Program as designed. Baseline media sampling for 2024 will include the launch of the Northwest Community Sampling Program for the tissue chemistry work of the baseline design. A separate tissues program will also start in 2024 and be completed by field consultants contracted by the NWMO. Additional work will include the continuation of atmospheric monitoring (air quality, noise, and light), hydrology studies, and further surface water quality sampling. 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 2022, NWMO's geoscience work at the potential repository site in this area continued, and main fieldwork activities for this phase of work were completed. This includes fieldwork activities such as the drilling, coring and testing of 2 deep boreholes (Figure 7-6), completing a 3D seismic survey in the area, installing a microseismic monitoring network, and installation of a shallow groundwater monitoring well network. As of the end of 2022, main fieldwork activities include ongoing maintenance, monitoring and groundwater sampling.

Figure 7-6: Example of Core from South Bruce Borehole 1

7.2.2 Environmental Program

Environmental field work in the SON-South Bruce area completed in 2023 included the surface water, hydrology, surficial soil and private well drinking water components of the Environmental Media Baseline Program (EMBP). The Year 1 Environmental Media Baseline Report and Environmental Media Change Assessment Report were both publicly released. Ongoing engagement related to the environment program, and field level oversight also continued. Details of the work completed in 2022 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 is undertaking the surface water quality component of the EMBP in the SON-South Bruce area. The SVCA completed the 2023 winter, spring, summer and fall surface water quality sampling campaigns at 34 sites throughout the Saugeen watershed (Figure 7-7). Fall 2023 marked the beginning of Year 3 data collection. Field sampling for the EMBP included phytoplankton, zooplankton, and periphyton, in addition to surface water sampling. eDNA and benthic invertebrates were collected for analysis by the University of Guelph to build their barcode sequence library to enable future biomonitoring using eDNA. This work will continue to be executed by the SVCA in 2024, as designed in the Environmental Baseline Monitoring Program.

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, and maintenance of a meteorological station in the Area of Interest (AOI) collecting continuous weather information.

Figure 7-7: SVCA Staff Collecting Plankton and Water Samples in Robson Lake, August 2023

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 7-8). Land permissions were obtained before entry to private, Municipal, County, Conservation Authority, and NWMO owned/optioned lands. In August 2023, Tulloch collected samples from 56 plots. Additional samples will be collected in 2024 to quality check results and fill any data gaps.

Figure 7-8: Tulloch Staff Collecting a Composite Surficial Soil Sample, August 2023.

7.2.2.3 Private Water Well Sampling

As part of the NWMO's environmental baseline monitoring program developed with the community, Tulloch Environmental was contracted to complete private water well sampling in the area near the potential repository site in the SON-South Bruce area (Figure 7-9). The program was voluntary and provided landowners an opportunity to find out their existing drinking water quality. A total of 27 wells were sampled in August 2023 and data will be shared directly with the landowners in early 2024.

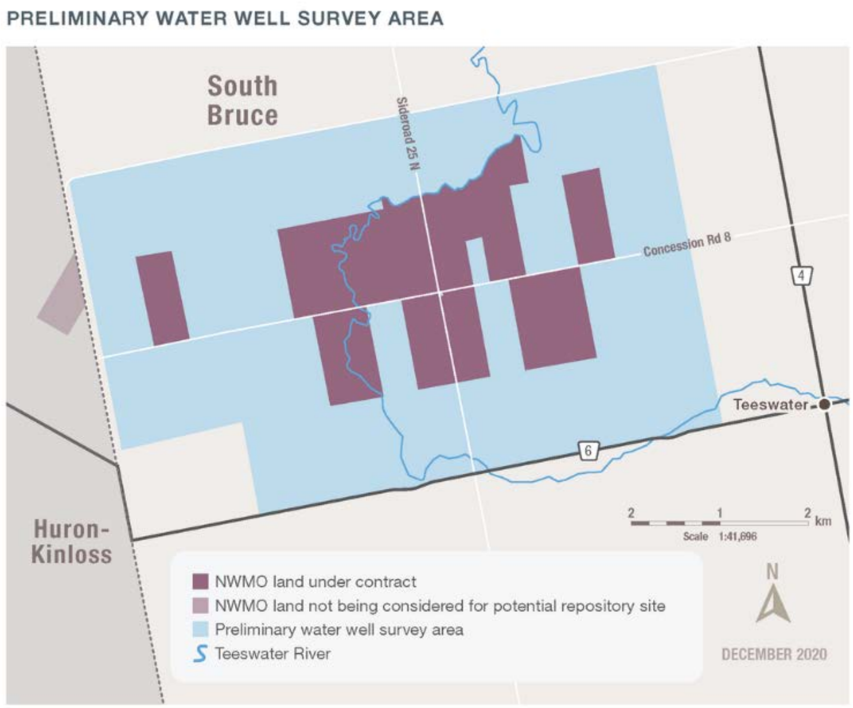


Figure 7-9: Map of the Area Where the 2023 Well Water Sampling Program was Offered to Property Owners near NWMO Acquired Lands

7.2.2.4 Compliance and Monitoring

The NWMO Environmental Program team also provided environmental monitoring and compliance oversight to contractors completing work in/near the SON-South Bruce area throughout the year. In-field contract oversight and inspections by the NWMO contract administrator were completed. In-field observations by a peer review team were also completed in 2023.

7.2.2.5 Engagement

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

7.2.2.6 Planned 2024 Work

Going forward into 2024 the environmental team aims to continue monitoring and executing compliance initiatives for work completed in the SON-South Bruce area, engage with community members as part of the baseline monitoring program, and continue executing the Environmental Baseline Monitoring Program as designed. Baseline media sampling for 2024 is planned to include surface water sampling, hydrology, soil sampling, and the launch of the atmospheric monitoring program. Biodiversity work is planned to resume in 2024 and will include the continuation of eDNA, aquatic habitat mapping, terrestrial ecosystem mapping, and significant wildlife habitat mapping programs, which are heavily dependent on private land access.

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APPENDIX: NWMO TECHNICAL REPORTS AND REFEREED JOURNAL ARTICLES

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