RD 2019 – NWMO's Program for Research and Development for Long-Term Management of Used Nuclear Fuel

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Nuclear Waste Management Organization

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ABSTRACT

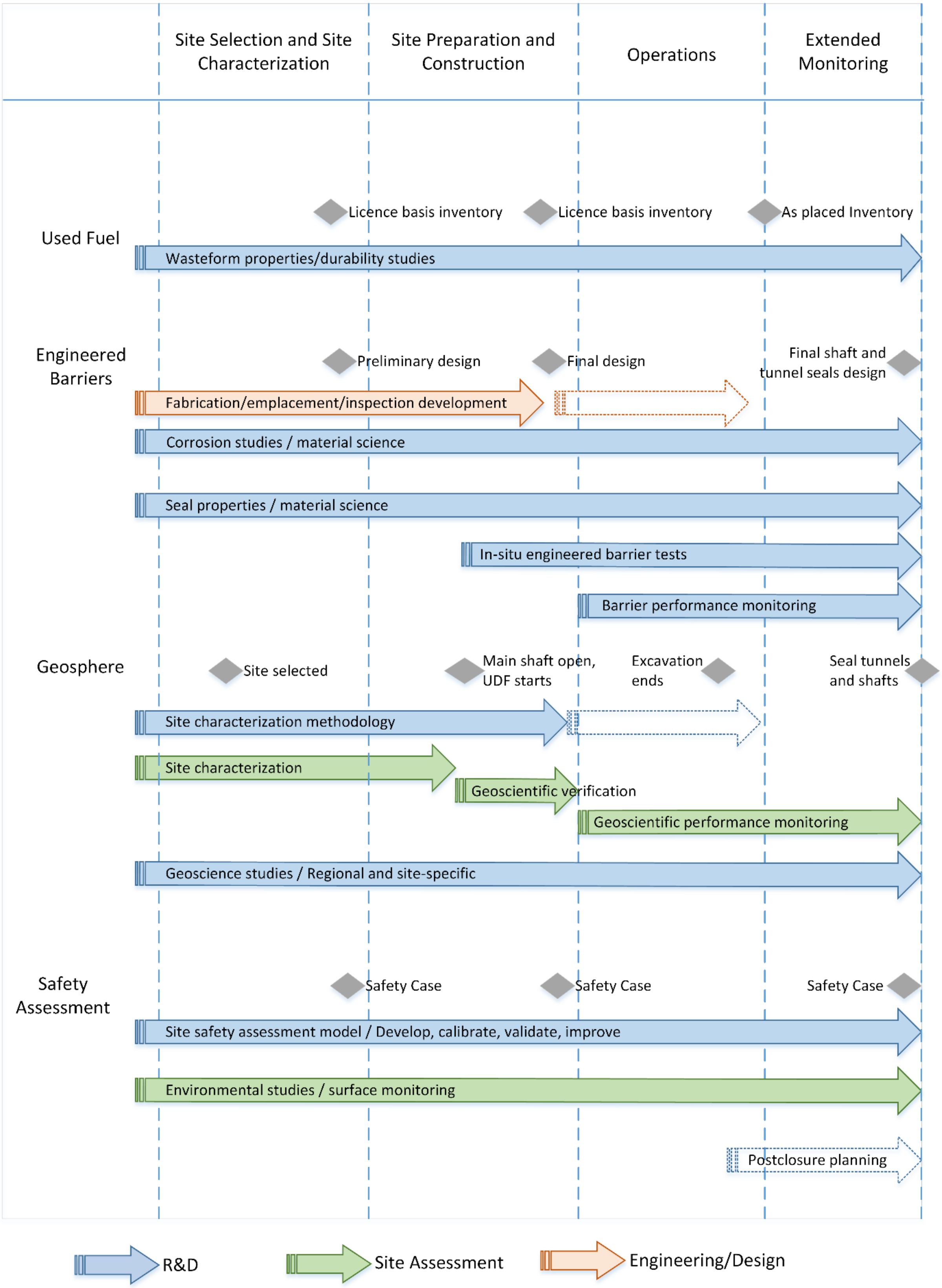
Summary

This report describes the major technical research and development activities of the Nuclear Waste Management Organization in support of the long-term management of Canada's used nuclear fuel through a Deep Geological Repository (DGR). It is complementary to NWMO activities in site selection, site characterization, design and engineering proof testing.

The full lifecycle of the repository can be considered as site selection and site characterization, site preparation and construction, operations, extended monitoring, closure and post-closure phases. The following figure provides a high level summary of some key milestones, and the broad nature of the research to be undertaken in the different phases to support these milestones, and the decision to close the repository. A key point is that underlying science studies will continue throughout the repository phases in order to support future licence decisions.

The report reviews the general status of understanding of used nuclear fuel properties, used fuel containers, sealing materials, geological processes, and safety assessment. It identifies directions for future research and development. Key near-term research topics identified in the technical chapters include the following:

- Further characterization and validation of waste inventory, including the incorporation of research fuels;
- Continued studies of the fundamental mechanisms important for wasteform and container durability;
- Scaled tests of copper-coated container and buffer durability under extended exposure to relevant thermal, physical, chemical, radiological and biological conditions;
- Acquiring information from candidate sites (e.g. rock properties, porewater chemistry), and incorporating these into the laboratory test programs;
- Further development and updating of regional geological information and models for the candidate siting areas to provide context to site-specific assessments.
- Further development and testing of reference models, notably Thermo-Hydro-Mechanical models, hydrological flow and transport, Discrete Fracture Networks, glacial systems, and an Integrated System Model, in part through participation in international projects.



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1 INTRODUCTION

1.1 Background

Nuclear power has been used to produce electricity in Canada since the 1960's. The CANDU (CANada Deuterium Uranium) reactor technology uses a natural uranium fuel bundle for power generation. When a fuel bundle is removed from a reactor, it is first placed in the irradiated fuel bay at the stations, a water-filled pool that provides shielding and cooling. After several years, the used fuel bundle is transferred into dry storage at or near the stations where it was produced.

Used nuclear fuel remains radioactive for a long period of time, and it must be contained and isolated from people and the environment. In 2007, the Government of Canada selected the Adaptive Phased Management (APM) approach for the long-term management of Canada's used nuclear fuel (NWMO 2005, NRCan 2007). APM is both a technical method and a management system. The technical end point is the placement of used nuclear fuel in a deep geological repository. The NWMO is responsible for implementation of APM.

Nuclear facilities, including those for long-term waste management such as a geological repository, are regulated by the Canadian Nuclear Safety Commission (CNSC). Licences are required from the CNSC for site preparation, construction, operation, decommissioning (closure and postclosure) and abandonment (i.e., release from CNSC licensing). Presently the NWMO is in a pre-licensing phase, considering potential repository sites and developing the design basis and community partnerships (NWMO 2018).

The NWMO's overall plan for implementation of APM is described in NWMO (2018). NWMO's technical work is conducted in cooperation with other waste management organizations, and consistent with NWMO's quality assurance program.

1.2 Scope

The purpose of NWMO's technical research program is to provide confidence in the repository safety case. The program also maintains expertise to support the repository development, including the ability to understand and apply research results performed elsewhere.

The document addresses technical research and development, identifying the priorities and directions at program level, with focus on geoscience, engineered barriers, and safety assessment. Specific activities, costs and schedules are not described in this document.

This document complements the NWMO Proof Test Plan, which addresses engineering design and demonstration, and the site specific Site Geoscientific Characterization Plan, which will be developed when a site has been selected.

The scope includes the full life-cycle of a repository, from the ongoing site selection through to closure. It provides more detail on the near-term, describes major R&D strategies, and outlines the NWMO plans to maintain a technical research program over the long term.

1.3 Planning Assumptions

The planning assumptions for the implementation of APM are as follows (from NWMO 2018):

a) Initiate APM site selection process in 2010 [complete].

b) Select preferred site around 2023.

c) Submit construction licence application documents around 2028.

d) Subject to receipt of licence, complete design and construction by 2043.

e) Operate facility for about 40 years.

f) Extended monitoring period of about 70 years.

g) Closure and decommissioning period of about 25 years.

h) Postclosure monitoring – indefinite.

1.4 Indigenous Knowledge

This document is focussed on technical research from a western science perspective. An important part of the NWMO APM project is to interweave Indigenous Knowledge with western science throughout the project. Initially, NWMO will focus on water, copper, clay and the rock as four topics that could provide a useful basis for this linkage.

1.5 Project Description

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 approximately 500 metres, depending upon the geology of the site, and consist of a network of placement rooms for the used nuclear fuel. Figure 1-1 illustrates these key elements of the repository.

Surface facilities provide processes and equipment for receiving, inspecting, repackaging, and moving used fuel to the main shaft to transfer underground, as well as emplacement in the repository.

Before being transported underground to the repository, the used fuel is placed into specialized containers and encased in a bentonite buffer box. Once underground, these buffer boxes are stacked (e.g., two high) in the horizontal placement room, and any spaces are backfilled with bentonite pellets.

A conceptual design of the repository and of the surface facilities, in a hypothetical site, is described in Noronha (2016).

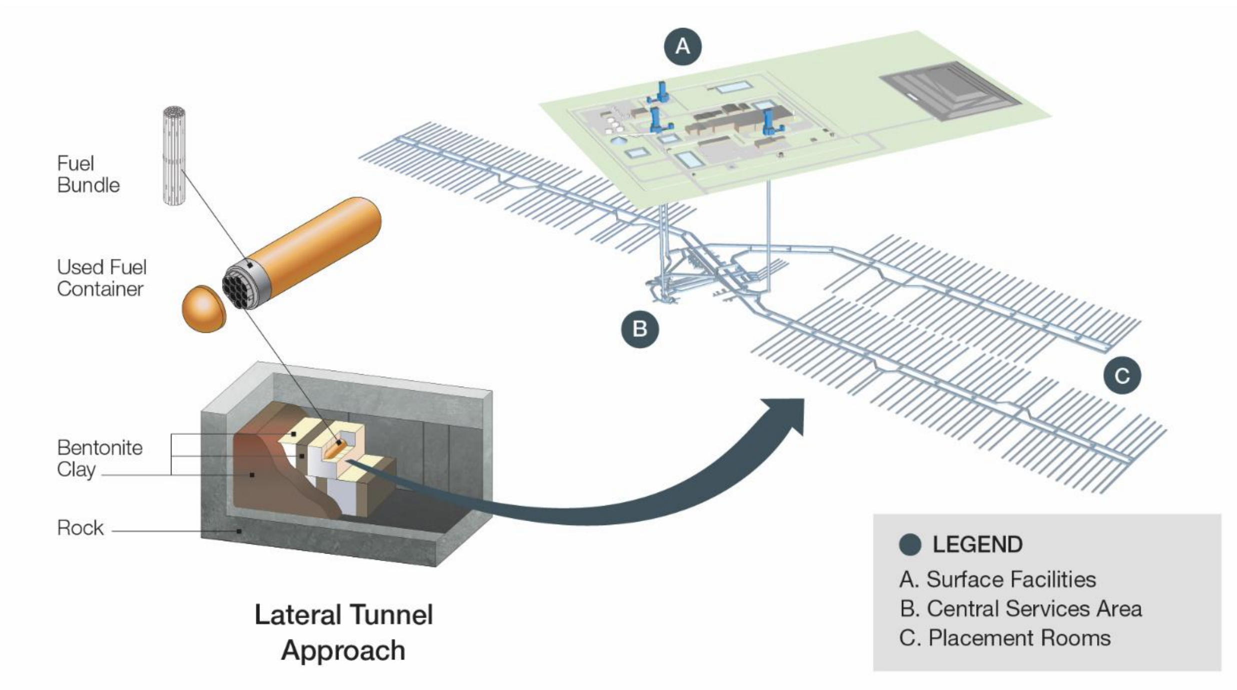

Figure 1-1: Illustration of the deep geological repository concept

1.6 Safety Case

The facility site, design and operation must protect people and the environment from harm. This safety must be provided during the full life-cycle of the repository, including construction, transportation, operation, and postclosure.

The safety case is the integrated set of reasons why the facility will isolate and contain the nuclear fuel wastes. The safety case for the deep geological repository builds on the concept of placement of the used fuel in a stable host rock, supplemented by other passive durable barriers, and by appropriate facilities and procedures for handling the waste in the near-term. The main safety attributes can be grouped as listed in Table 1-1.

Table 1-1: Main Safety Attributes

1. The used fuel wasteform is durable.
2. Container and sealing systems are robust.
3. The host rock provides isolation and containment.
4. The site geology has long-term stability.
5. The site supports safe construction and operation.
6. Repository construction, operation and closure support the long term performance.
7. The repository is robust to accidents and unexpected events.

The technical research provides confidence in these safety attributes through a program that improves understanding of relevant features, events and processes and/or through development or demonstration of the behavior of they system components. It is organized into the following topics:

- Waste inventory
- Wasteform durability
- Container durability
- Copper durability
- Placement Room seal
- Tunnel, shaft and other engineered seals
- Geosphere properties
- Geosphere stability
- Biosphere
- Monitoring
- Criticality and safeguards
- Safety assessment.

The next section of this report provides a more general technical framework for the technical research program. The state of knowledge and research directions for each of the above topics is then described in the following sections of this report.

1.7 References

Noronha, J. 2016. Deep geological repository conceptual design report – crystalline / sedimentary rock environment. Nuclear Waste Management Organization Report APM-REP-00440-0015 R001. Toronto, Canada.

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

NWMO. 2018. Moving Towards Partnership, Annual Report 2017. Nuclear Waste Management Organization. Toronto, Canada.

2 TECHNICAL RESEARCH FRAMEWORK

2.1 Historical Context

Canada and other countries have been studying the technical basis for deep geological repositories for decades.

Starting in 1978 and through the 1980s and 1990's, a substantive research and development effort was undertaken in Canada, primarily by Atomic Energy of Canada Limited (AECL), primarily at its Whiteshell Research Laboratories. It was assumed at that time that the site would be in the crystalline rock of the Canadian Shield, and the research was focused on that concept. A centerpiece of this program was the construction and operation of the Underground Research Laboratory (URL) in crystalline rock in the Lac du Bonnet batholith near Whiteshell (1985-2010) (Chandler 2003). Research also included deep boreholes near Atikokan and East Bull Lake in northern Ontario (Stone 1984). Supporting work was also carried out by Ontario Hydro, although that work was more related to preclosure operations.

From 1992 to 1998, a federal Environmental Review panel (the Seaborn Panel) reviewed the AECL/Ontario Hydro concept for a deep geological repository. The Panel provided a number of comments. Their key conclusion in 1998 was that the technical basis was adequate for that stage of the program but there was not sufficient social acceptance of the concept.

From the late 1990's, further development of the concept was transferred from AECL to the nuclear utilities, and in particular to Ontario Power Generation (OPG). Due in part to uncertainty over the future geologic setting and schedule for Canada's DGR, OPG shifted the ongoing research to place greater emphasis on universities, national laboratories, and joint projects at international research facilities including other national URLs. The Whiteshell URL was closed in 2010.

The federal Nuclear Fuel Waste Act was passed in 2002. As directed by the Act, the Nuclear Waste Management Organization (NWMO) was created, with all nuclear utilities as members. The NWMO conducted cross-Canada option studies from 2002 to 2005. Based on the conclusion of these studies, the federal government approved in 2007 the Adaptive Phased Management approach for the long-term management of nuclear fuel waste. This approach included both sedimentary and crystalline rocks as potential sites. NWMO was tasked with its implementation, including undertaking further research and development.

Starting in 2010, NWMO initiated a voluntary site selection program. Initially 22 communities expressed interest in learning more about the program. Based on initial technical and social assessments, these have been narrowed down. Presently there are siting areas in both crystalline rock of the Canadian Shield in northern Ontario, and in the sedimentary rock of the Michigan Basin in southern Ontario. The research program therefore includes conditions that might be expected in both crystalline and sedimentary rock sites. The NWMO is presently identifying specific potential siting areas within each of these broader siting area, and implementing more comprehensive site characterization in these areas.

In parallel to the used nuclear fuel program, OPG submitted an application in 2011 for site preparation and construction of a deep geological repository for low and intermediate level waste. This facility is proposed to be constructed at 680 m depth in the Cobourg limestone formation at the Bruce nuclear site. The development of this proposal included a substantive amount of research, including information from eight deep boreholes at the site, which is directly useful to NWMO potential sites elsewhere in southern Ontario.

In 2014, the NWMO conducted a detailed review of its used fuel container and engineered barrier system, and developed a new reference concept optimized for CANDU fuel, with several distinct features compared with the international concepts previously considered. Coincident with this, a non-nuclear proof test program was initiated to develop and demonstrate the ability to fabricate, handle and emplace the main components of the engineered barrier system.

The NWMO technical research program has been underway since 2007. This program provides support to all the NWMO technical activities, and in particular is complementary to the proof test program and the site characterization programs.

2.2 Program Governance

The NWMO technical research is conducted as per applicable requirements described in the NWMO management system. This system is compliant with CSA N286-12 (R2017) and ISO 9001:2017. Section 9.11 of CSA N286-12 requires that “Research and development activities in support of the radioactive waste facility shall be controlled.” Consistent with this requirement, the NWMO technical research is controlled. The management structure includes defined responsibilities and budget for technical research. Research is conducted under a technical research procedure, which complements and co-ordinates with other technical activities - notably design management and site characterization. The technical research plan is part of this managed process.

NWMO’s general quality expectations for technical research are defined in the APM Design and Technical Project Quality Plan. This covers topics including calibration of equipment, use of qualified staff, verification of work and development and use of qualified software (per CSA N286.7-16). Research at external organizations is carried out under project specific quality plans, which document how their work will adhere to the above quality requirements.

2.3 International Co-operation

The NWMO program continues to work collaboratively with other national and international organizations. It presently has cooperation agreements with eight countries, and is active in a number of joint projects and organizations including the International Atomic Energy Agency (IAEA) and the OECD Nuclear Energy Agency (NEA). DECOVALEX is an example of a long-running (25-year) joint project, in this case focused on understanding coupled thermo-hydro-mechanical-chemical processes in geological systems (Birkholzer et al. 2019). Specific cooperative programs are described in the following detailed technical sections.

One particularly important aspect of international cooperation has been participation in projects at various underground research laboratories (URLs). Table 2-1 provides a summary of several underground laboratories and projects particularly relevant to NWMO. A more complete list of underground laboratories worldwide is provided in NEA (2013).

Table 2-1: Some Major Underground Laboratories and Tests

Laboratory	**Major Tests (Partial List)**
Whiteshell Underground Research Laboratory (Canada)	
- About 420 m deep - Granitic rock of Canadian Shield - *[Chandler 2003]*	- URL Drawdown Experiment - Mine-By Experiment - Heated Failure Test - Connected Permeability Experiments - Buffer-Container Experiment - Isothermal Test - Moderately Fractured Rock Study - Tunnel Sealing Experiment - Quarried Block Radionuclide Migration Experiment - Enhanced Seal Project
Äspö Hard Rock Laboratory (Sweden)	
- About 460 m deep - Granitic rock of Fennoscandian Shield - *[SKB 2017]*	- Prototype Repository (full-scale, 6 heated containers, 2003-ongoing) - LASGIT (full-scale, 1 container in borehole, unheated, 2005-ongoing, gas injection studies) - DOMPLU (full scale concrete room plug, unheated, 2013-ongoing) - KBS-3H MPT (full-scale, 1 container in 15-m horizontal borehole, unheated, 2013-ongoing) - Canister Retrieval Test (full-scale, 1 container in borehole, 1999-2006) - TRUE Tracer Retention Understanding Experiment (50-m scale rock mass, 1996-2007) - Pillar Stability Experiment
Mont Terri Rock Laboratory (Switzerland)	
- About 300 m deep - Opalinus Clay rock formation - *[Muller et al. 2017]*	- FE (full scale, 3 heated containers, 2015-ongoing) - ICA (*in situ* corrosion test of nuclear waste container materials, 2012-ongoing)
Grimsel Rock Laboratory (Switzerland)	
- About 400 m deep - Granitic rock - *[Alonso et al. 2005]*	- FEBEX (full-scale, 18 m x 2.3 m, 2 heated containers, 1997-2016) - GAST (full-scale, tunnel seal, operating)
Meuse/Haute-Marne URL (France)	
- About 490 m deep - Callo-Oxfordian claystone	- ALC (full-scale, 25 m x 0.7 m ID, heated, operating)
ONKALO (Finland)	
- About 450 m deep - Granitic rock	- FSST (full-scale, non-nuclear container emplacement trials, 2018-ongoing)

The lessons learned from these international projects have contributed to our current understanding of key features and processes at large scales and in a variety of geological settings, have influenced our reference design and safety case basis, and have provided practical experience to qualify Canadian scientists and engineers for preparing for a Canadian DGR (e.g., see Box 5.1 in NEA 2013 on lessons learned from AECL's URL).

2.4 Technical Research Phases

Looking ahead, the technical program and related activities can be considered in the context of four phases:

- Site selection and characterization phase – Selection of a preferred site, and the development of a safety case, including preliminary design and environmental assessment, leading to a licence application for site preparation and construction..

- Site preparation and construction phase – Detailed design, construction of shafts and service area and main tunnels, and surface facilities. Application for operating licence.

- Operations, extended monitoring, decomissioning and closure phase – Operation of the facility, including construction of underground rooms, receipt of used fuel at facility, emplacement of fuel underground, and a period of monitoring while the rooms are sealed but tunnels and shafts remain open and monitored. It also includes the decommissioning and closure of the repository, including removal of any remaining equipment, sealing of tunnels and shafts, and the installation and operation of postclosure monitoring systems.

- Postclosure phase – Long term institutional control and monitoring of site.

Table 2-2 summarizes the main technical research and related activities within each of these phases. The nature of the technical program will evolve over the life cycle of the repository, but there is always a strong technical base to support the safety case for the DGR. While monitoring and research will likely continue during the postclosure phase, the research that supports the safety case must be sufficient to support the final decision on repository closure. Therefore the period covered in this report is up to the point of repository closure.

Table 2-2: Summary of Technical Program Elements Throughout DGR Lifecycle

Site Selection and Characterization Phase

- Core technical research - process understanding / capacity
  - Geoscience / Engineering / Safety Assessment / Environment
  - University based research
  - International URL joint projects
- Geoscience - methods for characterizing / assessing sites
- Proof test program
  - Small-scale to full-scale prototypes of critical components
- Site characterization
  - Geoscience and environmental field studies / baseline data
  - Environmental assessment
  - Development of Descriptive Geosphere Site Model and Geosynthesis
- Centre of Expertise
  - Large-scale mockup
- Preliminary Design
- Safety case to select site / support Site Preparation and Construction

Site Preparation and Construction Phase

- Core technical research
  - University based research
  - International URL joint projects
- Geoscience verification
  - Measurement / verification during shaft sinking
  - Verification at repository horizon
- Environmental field studies
  - Verification of Environmental Assessment predictions
- Underground demonstration
  - Underground Demonstration Facility
  - Engineering demonstrations - excavation / emplacement / retrieval
  - Long-term test initiation (e.g. materials, seals, performance)
- Safety case to support Operations

Operations, Monitoring and Closure Phase

- Core technical research
  - University based research
  - Center of Expertise through the Operations Phase
- Repository performance verification
- Monitoring of long-term tests including shaft seal performance
- Environmental monitoring and development of sensors and other technology for postclosure usage
- Retrieval / re-emplacement of active UFCs if needed from instrumented tests
- Closure and analysis of long-term tests, including shaft seal tests
- Safety case to support Closure

Postclosure Phase

- Installation / monitoring of postclosure monitoring systems

2.4.1 Site Selection and Characterization Phase

The main technical research activities in this phase are listed in Table 2-2. The main deliverable from this phase will be a safety case built around a site description, a preliminary design, an environmental impact assessment, and a safety report. These would support the application for a Site Preparation and Construction licence at the selected site.

The basic concepts for the safety case have already been established over the past decades of studies in Canada and internationally. Tables 2-3 to 2-5 identify some major studies within Canada (i.e., not including international projects) that have been conducted as part of the prior repository research program and which contributed to this knowledge base. Tables 2-3 and 2-4 summarize key studies relevant to the performance of the engineered barriers and the host rock, respectively. Table 2-5 summarizes key Canadian studies relevant to the construction of the underground facility.

The continued core technical research during the site selection and characterization phase supports the development of, and confidence in, the safety case that will be presented for the initial licence application. The basic concepts for the proposed DGR have been established over the past decades of research in Canada and internationally. The focus of the research is to improve our understanding of processes and mechanisms. This process understanding provide confidence in our ability to make statements about the long-term behaviour, building on the results from shorter-term laboratory experiments. It improves our knowledge of design and safety margins and reduces uncertainty in performance of the safety barriers.

The core technical research also ensures knowledge is continuously transferred to a new generation of technical staff. This is necessary because of the long timelines involved with this project, and provides capability to address new issues or questions that may arise.

The specific focus of this research will vary with time, although it will continue to address the main themes outlined in the next sections of this report. That is, there is expected to be ongoing research in the areas of wasteform durability, container durability, engineered barriers, geoscience, environment and safety assessment. However, the direction of the core technical research will be based on the specific design of the repository. It will be guided by engineering selection of materials, as well as site selection that affects environmental conditions.

The geoscience research during this phase is focused on understanding of geological processes, including in particular long-term geological stability, as well as the development of methods for site characterization.

As specific siting areas are identified, the geological work shifts to site characterization, which is addressed in the Site Characterization Plan. This site characterization is combined with the geoscience understanding developed through the research program to develop a regional and a site specific understanding. This understanding would be documented in two primary reports – a Descriptive Geosphere Site Model that describes the current site, and a Geosynthesis that describes the evolution of the site, both in the geologic past and into the future.

During this phase the proof test program will be active. This will develop and demonstrate the key engineering components or processes. It will evolve from scale-scale to full-scale non-nuclear prototypes and handling trials for critical components and materials. This work is described in a Proof Test Plan.

Engineering demonstrations are planned at surface facilities, including emplacement in a full-size (cross-section) emplacement room. Also during this phase, a Center of Expertise will be built in the vicinity of the selected siting area. While the scope of activities at this Center have not been finalized, they are expected to include some full-scale mockup tests.

Table 2-3: Summary of Major Canadian Repository Engineered Barrier Projects

Project Name [location]	**Time Frame**	**Key Features**
Whiteshell Underground Research Lab (WRL) [Canada]	1985-2010	- Underground Research Laboratory at Whiteshell, Canada. - Granite rock (Lac du Bonnet batholith) - Demonstration of underground excavation, monitoring, engineered barrier components/materials emplacement and performance - *[Chandler 2003]*
Heated Failure Test [WRL Canada]	~1994-1996	- Partial-scale in-floor borehole in granite - 0.6 m dia borehole, heated to 85°C - Rock response - *[Martino et al. 2001]*
Connected Permeability Expts [WRL Canada]	~1994	- Full-scale emplacement room excavation in granitic rock - One by drill and blast and one mechanically excavated - EDZ measurement - *[Chandler et al. 1996]*
BCE (Buffer-Container Expt.) [WRL Canada]	~1995-1997	- Partial-scale test of buffer and container, AECL concept, - 1.24 m diameter x 5 m borehole - In-situ in granite rock, 2.5 yrs, 85°C - *[[Martino et al. 2001, Dixon et al. 2002, Guo 2007]*
ITT (Isothermal Test) [WRL Canada]	~1995-2002	- Partial-scale test of buffer and container, AECL concept, - 1.24 m diameter x 5 m borehole - In-situ test in granite rock, 6.5 yrs, unheated - *[[Martino et al. 2001, Dixon et al. 2002, Guo 2007]*
TSX (Tunnel Sealing Expt.) [WRL Canada]	~2000	- Full-scale room seal tests, one concrete and one bentonite - 3.5 m high by 4.4 m wide elliptical tunnel - In-situ in granite, pressurized to 4 MPa, heated to 65°C, 2 yrs - *[[Martino et al. 2001, Martino et al. 2007]*
ESP (Enhanced Seal Project) [WRL Canada]	2010-present	- Full scale concrete shaft seal installed as part of decommissioning of Whiteshell URL - Performance of seal monitored - *[Dixon et al. 2018]*

Table 2-4: Summary of Major Canadian Repository Geoscience Projects

Project Name [location]	**Time Frame**	**Key Features**
Whiteshell Underground Research Lab (WRL) [Canada]	1985-2010	- Underground Research Laboratory at Whiteshell, Canada. - Granite rock (Lac du Bonnet batholith) - Demonstration of underground excavation, monitoring, engineered barrier components/materials emplacement and performance - *[Chandler 2003]*
Atikokan research site [Canada]	1980s	- Characterization of Eye-Dashwa pluton near Atikokan, Ontario - 5 boreholes from 200 to 1100 m; surface studies - *[Leech 1981, Stone 1984, Whitaker 1987]*
East Bull Lake research site [Canada]	1980s	- Characterization of gabbro-anorthosite rocks of the East Bull Lake Pluton, Ontario - 4 boreholes; surface studies - *[Raven et al 1987, Whitaker 1987]*
URL Drawdown Experiment [WRL Canada]	1984-1986	- Monitoring of shallow groundwater disturbance during shaft excavation and comparison with model - *[Davison et al 1995]*
MFR (Moderately Fractured Rock) [WRL Canada]	~1995-2005	- Hydraulic / solute transport test in ~50 m^3 volume of moderately fractured granitic rock - *[Vandergraaf et al. 2005]*
OPG Bruce boreholes BH1-8 [Bruce, Canada]	2006-present	- 8 deep boreholes at the Bruce nuclear site, for proposed OPG L&ILW DGR - Michigan Basin sedimentary rock - Borehole analysis, rock core analysis, monitoring - *[NWMO 2011]*
Ignace Wabigoon borehole IG-01 [Ignace, Canada]	2017-present	- 1000 m deep borehole near Ignace/Wabigoon - Canadian Shield crystalline rock - Borehole analysis, rock core analysis, monitoring

Table 2-5: Summary of Major Canadian Repository Construction Related Projects

Project Name [location]	**Time Frame**	**Key Features**
Whiteshell Underground Research Lab (WRL) [Canada]	1985-2010	- Underground Research Laboratory at Whiteshell, Canada. - Granite rock (Lac du Bonnet batholith) - Demonstration of underground excavation, monitoring, engineered barrier components/materials emplacement and performance - *[Chandler 2003]*
Mine-By Expt. [WRL Canada]	~1992	- Full-scale emplacement room excavation in granitic rock - 3.5 m diameter x 46 m long tunnel - Rock mechanical response to excavation and thermal loading, EDZ characterization - *[Martino et al. 2001, Read 2004]*
Connected Permeability Expts [WRL Canada]	~1994	- Full-scale emplacement room excavation in granitic rock - One by drill and blast and one mechanically excavated - EDZ measurement - *[Chandler et al. 1996]*
TSX (Tunnel Sealing Expt.) [WRL Canada]	~2000	- Full-scale room seal tests, one concrete and one bentonite in granite - 3.5 m high by 4.4 m wide elliptical tunnel - Pressurized to 4 MPa, heated to 65ºC, 2 yrs - *[[Martino et al. 2001, Martino et al. 2007]*
ESP (Enhanced Seal Project) [WRL Canada]	2010-present	- Full scale concrete shaft seal installed as part of decommissioning of Whiteshell URL - Performance of seal monitored - *[Dixon et al. 2018]*
UFC pressure test [USA]	2016, 2017	- Full-scale NWMO Mark II containers - Pressure tested (hydrostatic) to yield

There is no plan to build a site-specific underground research laboratory as part of the site selection and characterization phase. Information to support the safety case would be drawn in part from underground research carried out at the AECL Whiteshell URL and at other underground facilities noted in Table 2-1. Presently, NWMO is specifically involved in projects in both crystalline rock (e.g. at Äspö and Grimsel) and in sedimentary rock (e.g. at Mont Terri).

The NWMO also benefits from other underground research on Canadian geologies, including:

- Studies on the Eye-Dashwa Lakes pluton near Atikokan, northwestern Ontario (a massive, medium to coarse grained hornblende-biotite granite intrusion), including several cored deep boreholes. [e.g. Leech 1981, Stone 1984, Whitaker 1987]

- Studies on the East Bull Lake pluton near Sudbury, Ontario (a layered gabbro-anorthosite complex, crosscut by amphibolitic mafic dykes), including 4 cored deep boreholes. [e.g. Raven et al 1987, Whitaker 1987]

- Studies of the Cigar Lake uranium ore deposit in northern Saskatchewan, about 100,000 Mg of high-grade uranium ore at 450-m depth at the interface between the Archean Shield basement and overlying Proterozoic sandstone. [e.g. Cramer and Smellie 1994]

- Studies on the sedimentary rocks of southern Ontario through extensive surface and borehole studies of the Bruce site proposed for Ontario Power Generations deep geological repository for low and intermediate level wastes [e.g. NWMO 2011]

- Studies at the SNO Lab at Sudbury on effects of seismicity at a deep underground location. This work examined attenuation of seismic waves to 2 km depth in hard rock (glaciated norite and granitic rock). [e.g. Atkinson and Kraeva, 2010]

- Studies at Kidd Creek Mine in Timmons, which investigates the earth's oldest water, as well as the sulphur cycle of ancient microbiological species. [e.g. Lollar et al. 2019].

The NWMO will continue to explore opportunities to obtain further site relevant information prior to excavation of the repository level at the site. This could include:

- Installation of test modules into boreholes at candidate sites;

- Other analogs for site-specific conditions, including use of deep ocean test locations (pressure and salinity) and northerm permafrost sites (future climate hydrogeology).

2.4.2 Site Preparation and Construction Phase

During this period, the shaft, the underground central area, some part of the access tunnels, and the surface facilities will be constructed at the site. The main technical research activities in this phase are listed in Table 2-2. The main deliverable from this phase will be a safety case for an Operating licence.

During this phase, the site characterization work will transition into geoscientific verification. Specifically, during construction, this work would verify that the underground geology was consistent with expectations developed based on the site selection and characterization program. This will be based largely on measurements conducted during shaft sinking, and on verification of rock properties at the repository horizon. A geoscientific verification plan will be developed to support this.

Core technical research will continue in the main theme areas discussed in the previous section. It will continue to focus on understanding of processes and mechanisms, including university based research. It is expected that the underground excavations will generate site-specific information that will need to be incorporated into the models, and will also provide both material samples and test site opportunities for conducting core research.

The underground layout is planned to allow space for an Underground Demonstration Facility (UDF). The UDF would be one of the first facilities constructed once the shafts have been sunk to the repository horizon.

Figure 2-1 shows a conceptual repository layout, and the nominal locations of the two main testing areas. The early UDF would consist of one or more rooms excavated early in the construction phase after two shafts had been connected together. These rooms would be dedicated to initiating several of tests as soon as practical in order to provide information to help support the Operating Licence application, and then would continue to develop longer term data to support later licensing decisions including closure.

Potential early UDF tests include:

- In-situ rock mass behavior, such as diffusion properties
- Minimizing excavation damage zone
- Initiation of material tests, including for degradation of container and construction materials.
- Initiation of seal tests, including for degradation of sealing materials.

The intent would be to construct further trial emplacement rooms also as shown in Figure 2-1. These would be full-scale rooms, although possibly shorter length. They could be used for:

- Full scale excavation/placement tests for optimization and worker training, probably with non-nuclear containers.
- Pilot instrumented emplacement room (with dummy containers or real containers)
- Retrieval demonstration test.

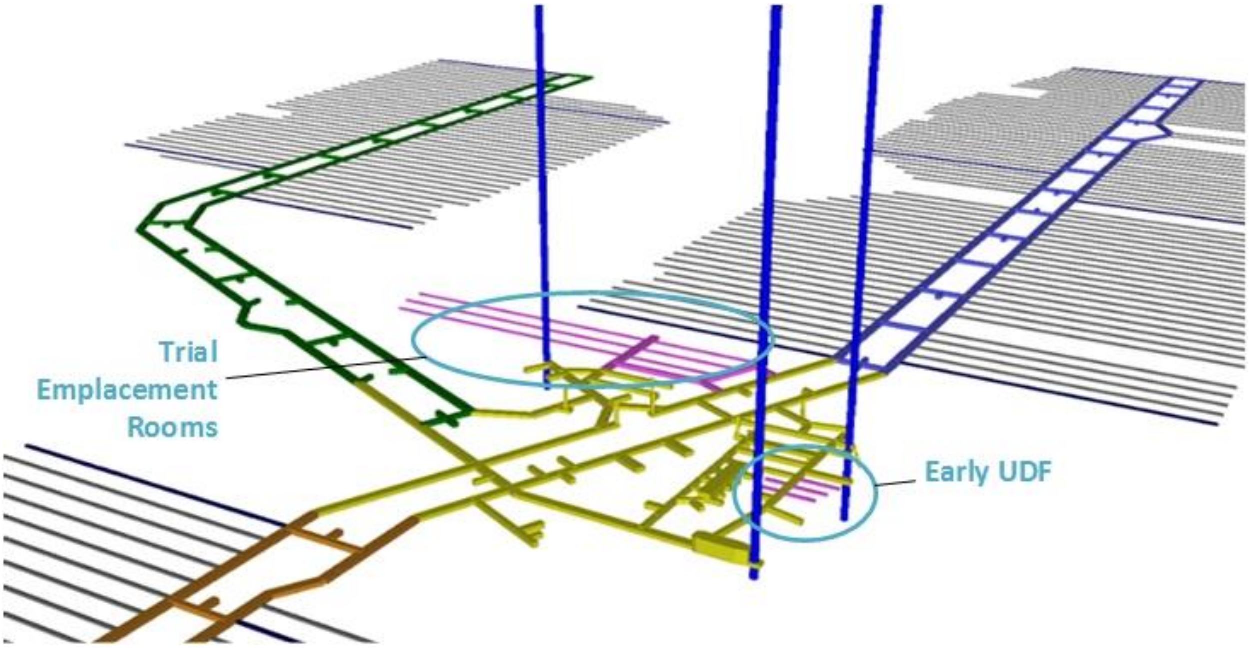

Figure 2-1: Conceptual repository layout showing location of rooms dedicated to testing

2.4.3 Operations, Monitoring and Closure Phase

As summarized in Table 2-2, after construction, a geoscientific monitoring program would monitor a variety of geoscientific indicators in and around the site to confirm that the site is responding as expected to the presence of the repository. This monitoring will build on baseline information collected during the site characterization and construction phase.

Core technical research will continue in the main theme areas to improve understanding, and to maintain appropriate knowledge of the safety case basis. This research will provide further confidence to support the eventual future decision to close the repository.

The overall lifecycle plan includes an extended period of monitoring of the repository before final closure. During this monitoring period, the emplacement tunnels are sealed and closed, but the access tunnels and shafts remain open. Key monitoring systems and long-term tests remain in place. These long term tests could include heated container tests, seal material compatibility tests, and possibly instrumented pilot nuclear tests. Prior to or during closure, these long-term tests would be decommissioned so that their information would be available to support the closure licence application. The respository monitoring systems would likely be scaled back, in consideration of both what could be relied on post-closure and in terms of minimizing possible impact on the safety barriers.

2.4.4 Postclosure Phase

As part of the repository closure, a set of monitoring systems will either already exist or be added. These will continue to be monitored. The nature of this monitoring and the nature of any ongoing technical research will need to be assessed closer to this time.

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3 WASTE INVENTORY

The nature of the wastes is the fundamental driver for the repository performance. The wastes need to be understood in terms of the following topics:

- Physical inventory
- Chemical composition
- Irradiation history
- Radionuclide inventory
- Heat generation
- Radiation fields
- Radionuclide distribution.

Most of this section discusses CANDU fuel, which is over 99% of the expected inventory. Non-CANDU fuel wastes are discussed separately. Wasteform durability and criticality are covered in other sections.

3.1 Physical Inventory

Currently there are about 2.9 million used CANDU fuel bundles. Based on the known plans for refurbishment and life extension, there could be about 5.5 million used CANDU fuel bundles (about 106,000 Mg heavy metal) from the current generation of nuclear power (Gobien and Ion 2019).

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

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

The Canadian used fuel inventory and forecast are updated annually by NWMO (Gobien and Ion 2019). A database with key information on fuel bundles produced to date is maintained by NWMO.

3.2 Chemical Composition

CANDU fuel is primarily pure UO_2 inside Zircaloy cladding. Estimates for the composition including trace elements are available in Tait et al. (2000). Measurements have recently been completed on a wide range of trace elements in unirradiated CANDU fuel bundles from the history of the nuclear power program and a range of suppliers. These results show a consistency in the chemical composition of the fuel and the Zircaloy over the duration of the CANDU program. The most notable change is a reduction in Ni impurity level in the Zircaloy after about 1971 (Liberda et al. 2019). Further work is needed on trace N and Cl levels in the unirradiated fuel, which are important as a source of C-14 and Cl-36 through activation.

3.3 Irradiation History

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

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

This information is currently being updated for used fuel generated in the past 5 years, and also to evaluate older fuel records that are not available electronically, as fuel irradiation data from the first decade or so of the CANDU reactor program is not fully available on an individual bundle basis. These represent less than 10% of the current fuel bundle inventory. These will be addressed by developing a statistical representation. The information will be periodically updated as new used fuel is generated in order to support assessment of the used fuel properties for future design and safety assessments.

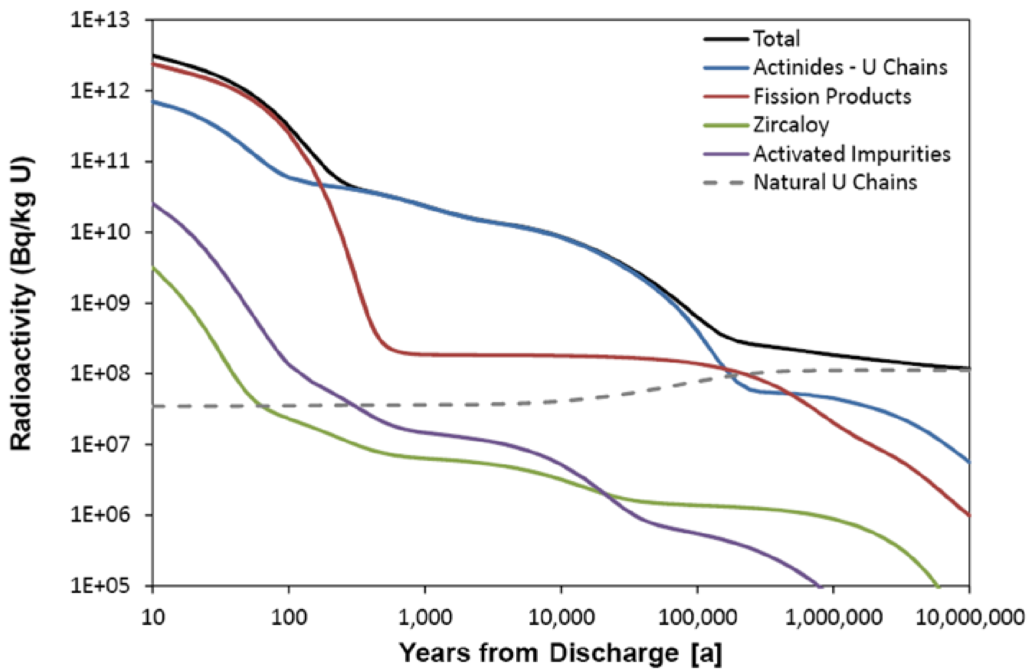
3.4 Radionuclide Inventory

The initial radionuclide content of used fuel is dependent on the duration and flux incident on the fuel during its residence in the reactor. The fuel burnup provides a good measure of this in-reactor exposure. This is the energy released per unit mass of uranium. At CANDU burnups of about 220-290 MWh/kgU, approximately 2% of the initial uranium (which includes U-235 and U-238) is converted into other elements through fission and neutron absorption.

When used fuel is first removed from the reactor it is highly radioactive, but its activity rapidly decreases, as shown in Figure 3-1. During the first 500 years radioactive decay is dominated by fission products, most of which are gamma emitters. Thereafter, the decay process is dominated by actinides, including uranium, which decay mainly by the emission of alpha particles. After about a million years, the total radioactivity in the fuel will have declined to levels that are equivalent to those found in naturally-occuring uranium ore bodies with similar amounts of total uranium.

The radionuclide inventory, radiation output, and heat output of used fuel as a function of time and burnup have been calculated using the industry-standard ORIGEN-S code (Tait and Hanna 2001). Due to the similarity of the CANDU reactors and the uniformity of the fuel, NWMO can define reference fuel bundles that bound the inventory results for all the CANDU stations at the same burnup (Tait et al. 2000). It is noted that, while there a possibility for contamination and tramp uranium on the outside of the bundle, this would have an insignificant impact on the overall inventory.

This calculation is based on a well-established software, ORIGEN-S/SCALE (Gauld 2011, Gauld et al. 2014), with cross-sections and decay data from international datafiles, notably the ENDF/B library (Brown et al. 2018, Chadwick et al. 2011). There is ongoing international work to improve the supporting information (nuclear cross-sections, decay rates, etc.) (Ilas et al. 2012, Francis et al. 2014, Gauld et al. 2014, Ilas et al. 2014, Skutnik 2017, Brown et al. 2018).



Note: Blue line (Actinides - U Chains) shows radioactivity of all actinides except U-238, U-235, U-234 and their progeny

Figure 3-1: Radioactivity of used CANDU fuel with a burnup of 220 MWh/kgU for times up to 10 million years. (Gobien et al. 2018)

Validation of the ORIGEN code for predicting radionuclide inventories in CANDU fuel showed that the calculated inventories agree well in general with the measured values, with differences generally well within the measurement uncertainties. The uncertainties in these inventories are discussed in Appendix A of Gobien et al. (2018). Studies have been done on evaluation of uncertainties on cross-sections, fission spectrum, neutron multiplicities and fission yields, as well as the impact of propagation of uncertainties, largely on LWR fuels (Fiorito et al. 2014, Leray et al. 2016, Leray et al. 2017).

The NWMO is presently updating its inventory basis using current CANDU-industry standard versions of the above software and libraries. This includes a re-evaluation of the validation basis for used CANDU fuel. In support of this, NWMO has recently conducted analysis of radionuclides in a CANDU fuel bundle end plate, and measured the trace element composition of a range of unirradiated fuel pellets over the history of the Canadian program.

The radionuclide inventory basis would be updated again periodically in the future, notably for input to safety assessments that support licensing applications. Although there are no specific plans, NWMO will consider opportunities for improving the validation database which may arise due to other activities, including periodic review of international groups reports and databases, for information relevant to the Canadian context, an example being the NEA's Expert Group on Assay Data of Spent Nuclear Fuel (NEA 2011, Michel-Sendis et al. 2017).

3.5 Heat Generation

Much of the decay energy is absorbed in the fuel itself, causing it to heat up. Immediately after being removed from a power reactor, a CANDU used-fuel bundle with a burnup of 220 MWh/kgU is producing about 27,000 watts of heat. After 30 years the same bundle would produce about 3.5 watts of heat. The thermal power is relevant for setting the repository design in order to maintain temperatures within design limits.

The thermal power is calculated based on the initial radionuclide inventory and known decay schemes and decay energies, from reference international datafiles. This information is mature for purposes of used fuel disposal. For example, validation tests on 10-30 year old LWR fuels indicate agreement within a few % (Ilas et al. 2014). Similarly, validation tests performed on Douglas Point 19-element CANDU fuel bundles showed generally good agreement, within a few % (Gauld and Litwin,1995). This decay heat decreases with time, and after about 30,000 years it becomes similar to the natural geothermal flux (NWMO 2017, Chapter 6; Perry et al. 2010).

Calculations for a conceptual repository at 500 m depth indicate container surface temperatures initially increase with time, reaching a maximum at about 45 years after emplacement, and returning to ambient within approximately 100,000 years (Guo 2016; NWMO 2017, Chapter 5). The maximum container design temperature is 100ºC. For a recent case study, the maximum container temperature was calculated as 85ºC (Guo 2016). The temperature of the used fuel within the container reaches a maximum temperature of 125ºC at about 15 years, decreasing to 112ºC at 50 years (Guo 2015). These peak temperatures would occur during the operational and monitoring period of the repository, so thermal monitoring of the repository during this period could provide direct confirmation of the heat generation.

3.6 Radiation Fields

The radiation fields in and around a container are calculated based on the initial radionuclide inventory and known decay schemes and decay energies, using international databases as noted above (e.g. ENDF/B library), and standard radiation transport calculations. This information is mature for species of interest for used fuel management (Wasywich 1993, Gauld and Litwin 1995, Tait et al. 2000, Tait and Hanna 2001, Børresen and Becker 2008).

Fuel radiation (alpha, beta, and gamma) field data at the fuel surface in water is available in Garisto et al. (2009). For a 30-year old 220 MWh/kgU burnup fuel, the alpha dose rate is 1.9×10^6 Gy/a, the beta dose rate is 2.7×10^6 Gy/a, and the gamma dose rate is 3.9×10^5 Gy/a. Separate calculations showed that neutron dose is not a significant contributor to the overall fuel radiation field from a radiolysis perspective.

NWMO is presently updating its reference fuel radionuclide inventory, and therefore also its radiation field basis. It would be updated again for the site-specific safety assessment to support a licensing application.

3.7 Radionuclide Distribution

Non-irradiated UO_2 fuel has a fluorite microstructure, and is a dense material with small amounts of residual sintering porosity from the fuel fabrication process. In the reactor, the UO_2 fuel undergoes a number of microstructural changes. The sintering porosity is largely eliminated, grain boundaries become more distinct, and volatile elements diffuse out of the fuel grains (Novak and Hastings 1991; Johnson and Shoesmith 1988).

More than 98% of the nuclides that are produced in the reactor remain within the UO_2 grains, very close to the location of their formation (Johnson and Shoesmith 1988). The elements produced by nuclear fission can be classified into three major groups according to their chemical behaviour (Johnson et al. 1994):

- Elements that are gaseous or semi-volatile at reactor fuel operating temperatures (e.g., Xe, Kr, Cs, I). While the fuel is in the reactor, a few % of these elements migrate from the UO_2 grains to the grain boundary, forming gas bubbles, and some of these further move into the fuel element void spaces (Johnson et al. 2005, Johnson et al. 2004).

- Elements that are non-volatile elements but have a low solubility in UO_2 (e.g., Mo, Ru, Pd). At reactor temperatures, small quantities of these elements diffuse out of the UO_2 grains and segregate as metallic alloy phases at grain boundaries (Novak and Hastings 1991). The majority of these elements, however, have low diffusion coefficients and remain trapped within the fuel grains.

- Elements that are compatible with the UO_2 crystalline structure, which remain in the lattice, within the UO_2 grains (e.g., lanthanide and actinide elements).

Figure 3-2 provides an illustration of the distribution of some of the fission products and actinides within a used fuel element.

Under CANDU conditions,it is expected that the radionuclides are relatively uniformly dispersed within the used fuel, and within the grains. “Rim” effects are observed to become significant at burnups in excess of 500 MWh/kgHM (Floyd 2001; Rondinella and Wiss 2010; Piro et al. 2016), which is much higher than the 220 MWh/kgHM typical of CANDU fuel.

The NWMO will continue to monitor the literature for improvements in understanding of radionuclide distribution in the fuel, but the primary factor important to the safety case is the amount that is on or near grain boundaries. This is discussed further in the next section on Wasteform Durability.

Radionuclides are also present in the Zircaloy cladding. Safety assessment case studies to date suggest that this inventory is not important in general to the repository safety case, certainly compared with the radionuclide inventory in the used fuel. Activation elements are expected to be uniformly distributed across the cladding. Some concentration of radionuclides may be expected on the cladding due to interaction with the fuel or coolant, as illustrated in Figure 3-2. The most important may be C-14, for which a significant fraction of its inventory in the Zircaloy may be located within the zirconium oxide layer on the Zircaloy surface according to some studies (Tanabe et al. 2009). The NWMO has recently conducted measurements on the activity of an irradiated CANDU bundle end plate; unpublished results indicate a thin and tightly adherent surface oxide, with notably higher U and Cm-244 levels, but not C-14, compared with the bulk metal. This will be further examined in the context of validation of inventory.

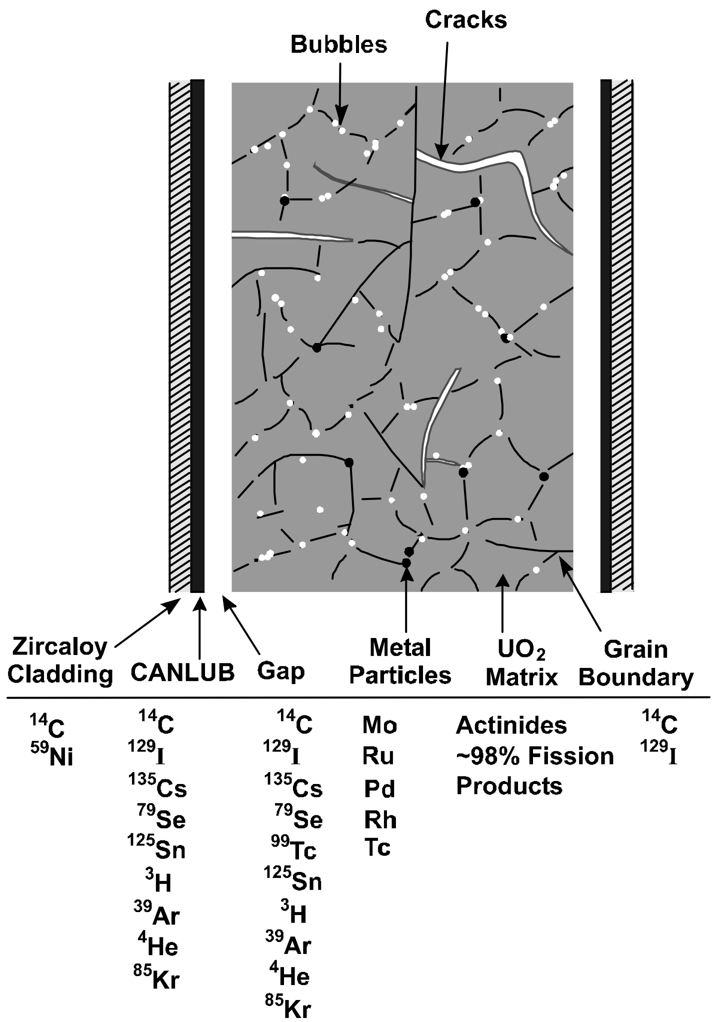


Figure 3-2: Distribution of some fission products and actinides within a used fuel element (not to scale), after Johnson et al. (1994).

The quantity of fission gases in the fuel-sheath gap has been measured on numerous used fuel elements. The measured fission gas release from CANDU fuel correlates with the peak linear power rating, not with fuel burnup. Specifically Figure 3-3 shows that fission gas releases from typical CANDU fuel bundles are < 1% for peak linear power values less than 44 kW/m, but increase sharply above that value. The median peak linear power for CANDU fuels is about 40 kW/m (based on Wilk 2013). Thus the peak linear power is relevant to release of radionuclides from the fuel, whereas the burnup is relevant to the total radionuclide inventory.

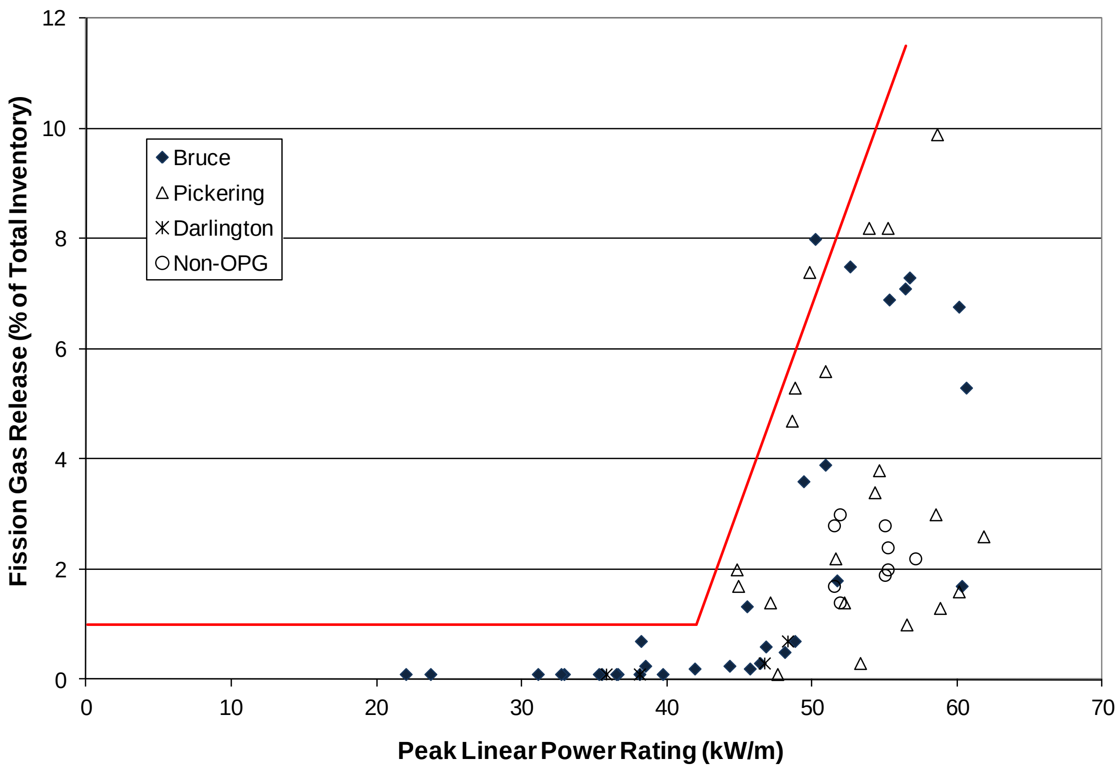


Figure 3-3: Fission gas (gap) release as a function of the fuel peak linear power rating for CANDU fuels with burnups less than 400 MWh/kgU (Gobien et al. 2018).

3.8 Non-CANDU Nuclear Fuel Wastes

The majority of used nuclear fuel in Canada is irradiated unenriched UO_2 from CANDU demonstration or power reactors. About 0.05% is research fuels largely owned by AECL. These are presently in a range of material forms and enrichments. Although a small volume, significant work is needed to characterize these waste materials and their final wasteform for acceptance in the APM DGR. Work to develop a more complete material inventory is currently underway at CNL.

Recently, there has been some interest in Canada in developing small modular reactors (SMRs). All of the currently proposed SMRs use non-CANDU fuel cycles, with some employing novel designs based on liquid fuels. Several designs are currently undergoing preliminary design reviews by the CNSC (CNSC 2018). Presently there is very limited information on the characteristics of these SMR used fuels. Work would be needed to characterize these waste materials and their final wasteform for acceptance in the APM DGR.

3.9 Research Program Summary

The waste inventory information is relevant for assessing the overall repository size, supporting the thermal design of the repository, and supporting the safety assessment.

Site Selection and Site Characterization Phase

The used CANDU fuel inventory is well understood. NWMO issues an annual report that summarizes the current physical inventory, and periodically reviews and updates the radionuclide inventory.

The radionuclide inventory is determined from the fuel irradiation history using qualified computer codes and nuclear property databases. The last published inventory summary was Tait et al. (2000). Currently work is underway to update this assessment.

Fuel irradiation data from the first decade or so of the CANDU reactor program is not fully available on an individual bundle basis, and older records are also not electronically available. These represent less than 10% of the current fuel bundle inventory. Work is presently underway to develop a statistical summary of this inventory.

About 1% of the fuel inventory is CANDU-like fuel from Canadian research and demonstration reactors. These are also natural unenriched UO_2 fuel bundles, but with modestly different physical geometry than current CANDU power reactor bundles. The number of these is known, but their irradiation history and inventory characteristics have not been described. Work has been initiated at CNL to develop this.

About 0.05% of the current fuel inventory is research fuels, mostly from the research program historically operated by AECL at its Whiteshell and Chalk River Laboratories. Some of these are fuels from research reactors, some are research materials, and some are CANDU fuels used for study purposes. These fuels have variable origins and characteristics. While high-level summaries are available, more work will be needed to assess their characteristics and determine how they would be made acceptable for the repository. CNL has initiated work on these inventories.

For SMR used fuel, the SMR vendor will need to determine the characteristics of these waste materials and their final wasteform for acceptance in the repository.

A database with information on fuel properties and data important for fuel handling, safeguards, and safety analysis will be needed. The current database, which includes burnup and power data, will be further improved and maintained to support the nuclear material accounting.

The NWMO will continue to monitor results or opportunities from other activities, including further validation tests, that may provide further supporting information on the used fuel content, and the radioactivity distribution in the used fuel.

Site Preparation and Construction Phase

While the broad inventory is well defined, further work may be needed to validate each individual fuel bundle or wasteform for handling at the Used Fuel Packaging Plant. This would be needed to manage the inventory in each Used Fuel Container and to meet safeguard requirements. This is discussed later in Section 13.

Operations, Monitoring and Closure Phase

The primary inventory activity will be tracking the characteristics of new used fuel generated during this period before it is accepted at the DGR.

There will also be opportunity during this period to verify the expectations for fuel decay heat rate, as the peak repository temperatures are expected to occur within this time frame.

Major Facilities

The main requirement is for access to laboratory facilities able to handle irradiated fuel in support of measurements to improve characterization and validation of radionuclide inventories. This is of particular relevance to non-CANDU fuels.

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4 WASTEFORM DURABILITY

This section discusses the need for research directed towards furthering understanding of the factors and processes that might cause the wasteform to change with time, and in particular to release radionuclides. The factors and processes considered here are discussed in terms of the following topic areas:

- Physical Integrity
- Used Fuel Dissolution
- Radionuclide Release
- Zircaloy Dissolution
- Radiation Effects
- Chemical Changes
- Biological Processes
- Gas Sources and Effects
- Solubility

These topic areas have been developed through consideration of the wasteform Features, Events and Processes (FEPs) such as identified in the NEA IFEP list (NEA 2019), and supplemented with other topic areas important to radionuclide release.

Nuclear criticality is discussed in Section 13 (Criticality and Safeguards).

The majority of Canada's used fuel is standard CANDU fuel bundles of the type illustrated in Figure 4-1; however, the stored inventory also includes small quantities of experimental fuel types (including some enriched in U-235) used by AECL. This latter fuel is currently the subject of characterization studies and is not explicitly included in the topic area discussions. Nevertheless, it is expected that most, if not all, of the statements made concerning the need for further research for CANDU fuel will also be applicable to the other fuel types. This will be confirmed as part of ongoing work when more information on these fuel types becomes available.

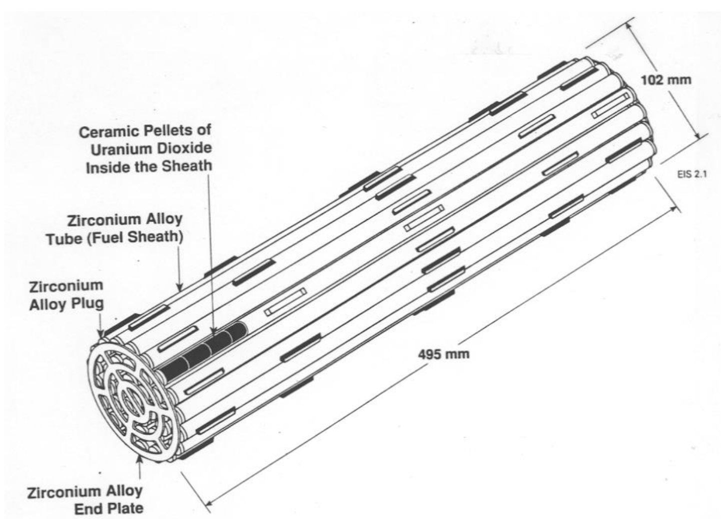

Figure 4-1: Typical CANDU Fuel Bundle

4.1 Physical Integrity

Earlier investigations have concluded that used CANDU fuel is unlikely to suffer significant mechanical degradation during an extended period of dry storage (100 years), since most of the known fuel and Zircaloy degradation mechanisms are not active under the conditions in which it is stored (Byrne and Freire-Canosa 1984; Lovasic and Villagran 2004; Lovasic and Gierszewski 2005). However, the Zircaloy structure, especially the endcap/endplate welds, may be susceptible to delayed hydride cracking (DHC) (IAEA 2019, Section 4.4).

Accordingly, a series of tests were conducted in 2007-2010 to establish the threshold value of key parameters (stress fields, stress intensity factors) for DHC to occur in CANDU fuel bundles. These threshold values were then compared to modelled parameter values under dry storage conditions, to allow prediction of bundle long-term behaviour. Bending load tests were also performed on unirradiated single fuel elements from typical 28- and 37-element CANDU fuel bundles. Details of the validation of model results are reported in Lampman et al. (2008, 2009).

The findings from this program, completed in 2010, indicate that DHC will not affect the long term integrity of most CANDU fuel in dry storage. The results are summarized in Lampman and Gillespie (2010).

It is therefore expected that the fuel bundles will be mostly intact during the handling phase. However it is possible that some fuel bundles would become damaged during transportation and handling at the DGR site, and therefore these operations will be planned assuming the potential for fuel to be damaged.

The postclosure safety assessment assumes that, once in the UFC, the fuel cladding does not act as a barrier to radionuclide release. Consequently, there is no need for future major research on cladding integrity for postclosure safety. However, there may be opportunities to better quantify this behaviour and provide context for the degree of conservativism in the safety assessment models, and to better inform the design of the fuel handling systems prior to placement in the DGR.

For bundles that are not intact, the most likely damage is separation of fuel elements from the end plates, with no breach of the fuel cladding. This has already been observed in CANDU fuel bundle tests, and there are a small amount of such separated fuel elements in the wet fuel bays at the various stations. The reference plan is to put these elements (dry) into a steel can that is slightly larger than the dimension of a fuel bundle. Work has started on the detailed design of these cans, with the intent to use them first in the decommissioning of the Gentilly-1 wet bay. The Used Fuel Packing Plant (UFPP) at the DGR site will be equipped to handle these cans, and to place them in appropriately sized used fuel container (UFC) inserts. Consequently, while the number of such cans may increase if the fuel degrades more quickly than expected, the primary impact is on cost and throughput.

The NWMO will continue to monitor the literature on fuel cladding integrity. This is a topic of interest for other countries as well, and with their higher burnups their conditions may provide bounding information. The integrity of CANDU fuel bundles will be monitored opportunistically during the siting phase if stored used fuel is transferred to other containers or other storage locations. It will be directly monitored during actual operation of the facility, as the used fuel is transferred to the UFPP and repackaged into the UFCs.

4.2 Used Fuel Dissolution

CANDU fuel is fabricated from high-purity UO_2. Under the reducing conditions expected in the repository, the solubility of UO_2 is very low (Neck and Kim 2001; Rai et al. 1990; the solubility of UO_2 was predicted to be ~$3x10^{-9}$ mol/L in crystalline rock in Canada by Duro et al. 2010); whereas under oxidizing conditions the solubility of UO_2 is many of orders of magnitude greater.

The groundwater entering a breached container would be anaerobic under most scenarios of interest, including defective containers, mechanical stress or faster corrosion. However, radiolysis of this water due to the fuel radioactivity will produce a variety of chemical species including oxidants in this water. In the presence of oxidants, the dissolution of UO_2 is a corrosion reaction, in which the oxidant is consumed to convert the insoluble U(IV) to the much more soluble U(VI) (as UO_2^{2+}). The rate of this reaction will depend on redox conditions, including in particular the strength of the radiation fields from the fuel (Figure 4-2) as well as the carbonate concentration in the groundwater which will complex with UO_2^{2+} (Grenthe et al. 1992). It will also be influenced (suppressed) by H_2 produced by the corrosion of the inner surface of the steel container and by water radiolysis (Shoesmith 2008; Liu et al. 2017; Liu et al. 2016). The long-term suppression effect of H_2 produced by water radiolysis on the oxidation of UO_2 (uraninite ore deposit) under anoxic conditions was demonstrated from the Cigar Lake Natural Analogue study (Bruno and Spahiu 2014).

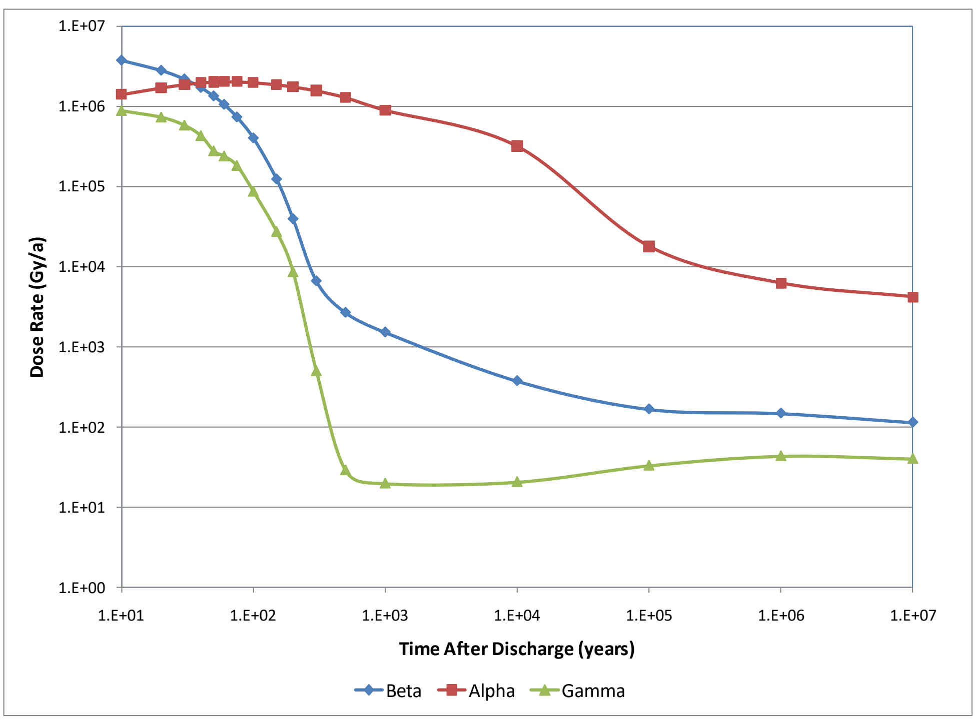

Figure 4-2: Alpha, Beta and Gamma Dose Rates to Water near a Used Fuel Bundle with a Burnup of 220 MWh/kgU as a Function of Fuel Discharge Time

A good understanding of used fuel dissolution under repository conditions has been obtained through the studies undertaken at AECL in the 1980s and 1990s, and subsequently through the NWMO sponsored Industrial Research Chair in Nuclear Fuel Waste and Waste Container Corrosion at Western University, as well as internationally (Liu et al. 2016; Wu et al. 2014; He et al. 2012; Shoesmith 2007; Werme et al. 2004). This knowledge forms the basis of the used fuel dissolution model used in safety assessment studies (see Gobien et al. 2018, Appendix B). In this model, the fuel dissolution rate depends on the strength of the alpha, beta and gamma radiation fields (see Figure 4-2) and the fuel surface area. At very long times, after decay of the alpha field, chemical processes control the rate of fuel dissolution. The ability of hydrogen to suppress the dissolution process is not included.

The current research work is focused on the development of an improved database for the model developed to describe the fuel behaviour inside a failed container. Presently, the emphasis is on the following areas:

(i) the decomposition kinetics of H_2O_2 on UO_2 fuel pellets, and its effect on the fuel dissolution process;
(ii) mechanisms of H_2 interactions with UO_2 surfaces in the presence of radiation; and
(iii) establishing the variability of UO_2 reactivity for CANDU fuel pellets.

While many of the details of the used fuel degradation processes are now sufficiently understood, continued research is planned to further improve understanding, and to improve confidence in the long-term behaviour. In particular, areas of future study would be to (i) evaluate the UO_2 behaviour using actual site groundwater chemistry once that is known; (ii) determine whether the radiolytically-driven fuel corrosion process is sensitive to the high salinities expected in groundwaters; and (iii) examine the possibility of model validation using natural analogue data. It may be noted that the H_2 effect on suppressing dissolution is not currently included in NWMO safety assessments.

An additional area of study will be the durability of non-CANDU used fuel wastes from prior AECL research and demonstration reactors. These wastes are presently in a variety of forms, including UC, USi and U metal. On time frames relevant to a repository, some of these materials may substantively dissolve or degrade if in contact with groundwater. Therefore, further understanding of the rates of dissolution of these wastes, and of alternative more durable forms they could be transferred into (e.g., glass, oxides), would be required to support the inclusion of these materials in the DGR safety case.

4.3 Radionuclide Release

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

Studies of the interaction between used fuel and groundwater done over the last 30 years have established that radionuclide releases occur via two primary mechanisms acting on different time scales. These mechanisms are known as “instant release” and “congruent release” (Johnson et al. 1994; Nykyri et al. 2008).

Instant release is the relatively rapid release of a small percentage of the inventory of those radionuclides (such as isotopes of Cs, I and Xe) that reside in the fuel-sheath gap and at the fuel grain boundaries. These nuclides can be quickly accessed by water once the fuel sheath fails (Johnson et al. 2005, 2004; Werme et al. 2004; Garisto et al. 2004).

The second and much slower process is the congruent release of the radionuclides from the UO_2 fuel matrix, which occurs as the fuel grains corrode or dissolve.

4.3.1 Instant Release

The portion of each radionuclide inventory that is available for instant release is called the instant release fraction or IRF.

Instant release fractions for elements in CANDU fuels are primarily based on the work of Stroes-Gascoyne (1996). The instant release fraction information from non-CANDU fuels has also been considered in this assessment (Johnson et al. 2004, 2005; SKB 2010).

The data shows that the instant release fraction scales with fission gas releases, which in turn, is known to increase with peak linear power as illustrated in Figure 3-3. This is because higher power means higher fuel temperature, and therefore faster migration of gases and other elements to grain boundaries where they are available for release as the IRF.

The fuels used in the experiments of Stroes-Gascoyne (1996) have peak linear power ratings that are generally higher than those expected for typical CANDU fuel. For example, only about 14% of CANDU used fuel bundles have peak linear power ratings greater than 42 kW/m (Wilk 2013), whereas in the work of Stroes-Gascoyne (1996) 57% of the fuels had peak linear ratings greater than 42 kW/m. Thus, measured instant release fractions from Stroes-Gascoyne (1996) should be conservative, based on the relationship between fission gas releases and peak linear power rating, as described below.

For light-water reactor fuel, fission gas releases are independent of fuel burnup for burnups less than about 1000 MWh/kgU with an increase seen at higher burnup values (Johnson et al. 2004). Because CANDU burnups are roughly four times lower than this threshold value, and because there is no correlation between fuel burnup and linear power rating, fission gas releases from CANDU fuels are not correlated to fuel burnup.

There is direct experimental data for key radionuclides in used fuel, including I and C. For radionuclides other than these, the instant release fractions have been estimated using conservative assumptions, information from LWR fuels, and chemical analog arguments (Gobien et al. 2018, Section 4.5). For these other elements, for which less data is available, sensitivity studies (e.g., NWMO 2017, Section 7.8.2.3.1) show low sensitivity of dose consequence to reasonable assumed variations in their instant release fractions.

Gap and grain boundary inventory predictions made with CANDU reactor safety codes such as FEMAXI have also been examined to determine if they can provide useful information for predicting IRFs for fuels with different power ratings and burnups. However it was concluded that there were too many undefined parameters for the models to have predictive value for radionuclides other than fission gases (Iglesias et al. 2011).

In the postclosure safety assessment, all contaminants on surfaces are assumed released instantly once groundwater contacts the fuel. The fuel is conservatively assumed to be highly fractured, so that all gap and grain boundaries present in the fuel are assumed immediately exposed to groundwater.

Based on the existing understanding, the postclosure safety assessment approach and the illustrative sensitivity results, there is no planned major research on the topic of instant release fractions. However, given the importance of this data to the overall safety assessment, the literature and opportunities to improve current understanding will be monitored.

4.3.2 Congruent Release

The IRF represents the fraction of the radionuclide inventory that is accessible in grain boundaries and in gaps. The remainder of the radionuclides in the fuel, in excess of 98%, is contained within the UO_2 fuel grains in used CANDU fuel at time of disposal.

These radionuclides are not mobile within the UO_2 grains at the relatively low temperatures experienced by the fuel (less than about 150^{o}C during dry storage, and cooling over time after disposal).

In the postclosure safety assessment, these contaminants are released commensurate with the dissolution rate of the fuel. This is assumed to start immediately after the container is breached, with no allowance for time to fill container with water nor for the protective Zircaloy cladding to fail. Under reference conditions, used fuel is estimated for safety assessment modelling to take about 10 million years to dissolve, and therefore the residual radionuclides are released on this timescale. This is fast compared to natural uranium ore bodies, some of which such as Cigar Lake are over 1 billion years old without evidence of appreciable uranium release rates (although at much lower radioactivity levels) (Liu et al. 1996).

Going forward, because congruent release is so closely related to used fuel dissolution, future research is the same as that described for used fuel dissolution in Section 4.2.

4.4 Zircaloy Dissolution

The Zircaloy cladding is potentially important as a barrier to prevent contact of fuel with groundwater in a failed container, and as a source of radionuclides. The latter are primarily due to activation of the Zircaloy itself.

Pitting/crevice corrosion of Zircaloy is possible in the presence of radiolytically-decomposed saline groundwaters, particularly if container failure occurs early while radiation dose rates are high, and brittle hydrides can also form if the Zircaloy is exposed to sufficient hydrogen gas, potentially arising from corrosion of the steel container. Due to these processes, no credit is taken in the postclosure safety assessment for the integrity of the fuel cladding. And consequently it is not necessary to undertake detailed modelling or research on fuel cladding integrity.

However these processes do not lead to rapid dissolution of the bulk zircaloy itself, which is necessary for the release of the contained activation radionuclides. Zircaloy is a corrosion-resistant alloy which degrades at a slow rate under reducing groundwater conditions (Shoesmith and Zagidulin 2011).

In postclosure safety assessment case studies, screening exercises have been performed to identify contaminants in the Zircaloy that could potentially be significant to the overall consequence. Typical results (NWMO 2017, Section 7.6.2) show that none are especially significant, even under various sensitivity cases. The most important may be C-14, for which a significant fraction of its inventory in the Zircaloy may be located within the zirconium oxide layer on the Zircaloy surface (Tanabe et al. 2009). This C-14 in the oxide layer is therefore conservatively assumed to be instantly released when water contacts the cladding.

Given the above, there are no experimental programs planned on the subject of improving the understanding of Zircaloy dissolution and Zircaloy instant release fractions. However the literature will be monitored, as well as opportunities to improve current understanding.

4.5 Solubility

Radionuclide solubility will limit the maximum concentrations of radionuclides within or near a failed container, with the concentrations being used as the source term for radionuclide transport calculations. Radionuclide solubilities are calculated by geochemical modelling using thermodynamic data under relevant geochemical conditions. These data are compiled in quality-controlled thermodynamic datasets.

Two approaches are used for activity coefficient correction for saline solutions:

(1) The SIT (specific ion interaction theory) approach which is valid for electrolyte solutions with ionic strength up to 3-4 mol/kgw; and
(2) The Pitzer approach which is valid for electrolyte solutions with ionic strength up to 20 mol/kgw.

The SIT model would be appropriate for solubility and speciation calculations for deep groundwater at repository depth in crystalline rocks in Canada, whereas the Pitzer model would be appropriate for deep groundwater at repository depth in sedimentary rocks in Canada.

A potential acceptable SIT-based reference thermodynamic dataset is Thermochemie (https://www.thermochimie-tdb.com/), developed by ANDRA. It builds on the widely-regarded NEA Thermodynamic Database (https://www.oecd-nea.org/dbtdb/), which mainly focusses on a subset of elements of potential interest. A public version of Thermochemie is available. This dataset, with some enhancements, would likely be sufficient for an NWMO crystalline rock site.

There is no widely available Pitzer-based reference dataset that addresses the majority of elements of interest to the NWMO. Some Pitzer-based thermodynamic datasets include a US Yucca Mountain project dataset which is no longer maintained, a US WIPP project dataset, and a German THEREDA dataset. A state-of-the-art report on high-ionic strength systems to identify the data gap for Pitzer ion interaction parameters will be released by the NEA TDB project in 2020.

To aid in the generation of thermodynamic data needed for solubility calculations, the NWMO has for many years supported the NEA Thermodynamical Database project. This project, currently supported by 15 international participants, has the objective of compiling and reviewing thermodynamic data for chemical elements of interest in safety assessment.

Additionally, the NWMO is co-sponsoring the NSERC/UNENE Senior Industrial Research Chair in High Temperature Aqueous Chemistry at the University of Guelph, the focus of NWMO interest being the generation of high quality thermodynamic data for contaminants of interest at high temperatures and high salinities. Thermodynamic properties of (1) uranyl carbonate, chloride and hydroxide complexes, and (2) lanthanum and thorium chloride and hydroxide complexes in saline solutions are currently being investigated.

Going forward, the solubility work program will continue to develop data as needed for Canadian conditions, and participate in international reference database projects such as the NEA Thermodynamical Database project.

4.6 Radiation Effects

Radioactive decay of the used fuel results in alpha, beta and gamma radiation, together with a small number of neutrons and the creation of decay products (notably He atoms and radionuclide progeny). It also causes decay heating (see Section 3.5).

Alpha decay in particular could damage the fuel through radiation damage and/or accumulation of helium atoms in the fuel, potentially leading to fuel lattice swelling, embrittlement, gas release and fuel sheath stress. Helium bubble formation is observed above $5x10^{18}$ He atoms/g (Wiss et al. 2014, Pencer et al. 2017). Fuel lattice swelling may start at this point, and reach a few % at concentrations of $4x10^{20}$ He atoms/g (Pencer et al. 2017). CANDU natural uranium fuel would reach about $5x10^{18}$ He atoms/g after about 10,000 years, and about 10^{19} He atoms/g in about 1 million years (Pencer et al. 2017). Higher levels would occur in LWR fuels due to their higher burnup; e.g. about 45 GWd/tU for typical LWR fuel compared to 10 GWd/tU for a typical CANDU fuel.

Some studies on LWR UO_2 spent fuels, indicate that the quantity of alpha-decay helium is not sufficient to induce micro-cracking of grains in the pellet core even at LWR burnups (Ferry et al. 2008). Natural analogue evidence also suggests that alpha radiation damage would not cause used fuel to crumble from accumulation of gases, even after very long times (Janeczek 1999; Jensen and Ewing 2001). However Wiss et al. (2014) acknowledged the potential to retain the helium within the microstructure, but considered that alpha-damage could weaken the matrix and that safety assessment should consider the effect of helium release from LWR fuel. Pencer et al. (2017) concluded that significant effects from alpha-damage in natural uranium fuels would not be expected for at least 10,000 years.

A related question is whether the alpha-radiation damage would increase the rate at which volatile species move from within the UO_2 fuel grains to the grain boundaries, a process called athermal diffusion (Poinssot et al. 2005, 2006; Ferry et al. 2004; Lovera et al. 2003). For high burnup LWR fuels (> 45 GWd/tU), Poinssot et al. (2006) predicted that by this mechanism, 5% of the radionuclide inventory in fuel could be transported to the grain boundaries after 10,000 years, and that up to 7% could be transported after 100,000 years. Desgranges et al. (2003) concluded however that alpha self-irradiation would not induce significant modification of gaseous fission products under storage conditions. In addition, work by Ferry et al. (2008) and references therein indicates that the enhanced diffusion for fission product atoms under alpha self-irradiation in LWR fuels is about three orders of magnitude lower than the previous upper estimate. With this new value, and also in the context of lower burnup CANDU fuel, the contribution of alpha self-irradiation enhanced diffusion to the distribution of radionuclides within the fuel, and in particular to instant release fractions of fission products, is considered negligible.

In the postclosure safety assessment, the used fuel is initially (i.e., at the time of placement in the repository) assumed to be in a fragmented state with no intact Zircaloy sheath and with conservative values for instant release fractions. There is no expectation that the fuel or the Zircaloy sheath is containing fission gases. Furthermore, sensitivity studies (e.g., NWMO 2017, Section 7.8.2.3.1; NWMO 2018, Section 7.8.2.3.1) illustrate the low sensitivity of dose consequence to reasonable variations in the instant release fractions and the fuel dissolution rate.

Based on the current understanding and treatment in the safety case, no future research on radiation effects on radionuclide or fission gas release are planned. Opportunities to improve current understanding would be monitored however. Radiation effects on used fuel dissolution are of continued interest as described in Section 4.2.

4.7 Chemical Changes

UO_2 is a stable material under reducing conditions. The used fuel is expected to remain stable over one million years, if not exposed to radiolytic oxidants, oxygen or aerobic conditions. This is consistent with natural uranium ore bodies such as Cigar Lake, which are often UO_2 (uraninite).

4.8 Biological Processes

A wide range of microbes will inevitably be introduced into the repository during its construction and operational phases. Some could be present in the UFCs as delivered to the repository, whereas others could be introduced earlier, as the placement rooms are excavated. Oxygen in the repository at the time of closure will promote growth of some aerobic microbes, but anaerobic species could be viable in the long term once anaerobic conditions are established. Growth also requires the presence of suitable nutrients.

Within the closed used fuel container, microbial activity is expected to be low or non-existent (intact or defective) because of the limited organic and nutrient sources present, low water content, high initial temperatures, and high initial radiation fields.

Furthermore, UO_2 is a relatively thermodynamically stable material. There is extensive evidence that U^{VI} (as UO_2^{2+}) can be reduced microbially to nanoparticulate $U^{IV}O_2$ in natural sediments, a process known as biomineralization. In fact this process has been claimed as a mechanism for the formation of U^{IV} ore bodies. There is also a considerable literature on bioremediation of U contaminated groundwater systems. These studies indicate that that microbial effects will be neutral or exert a retarding effect on fuel dissolution once reducing conditions are established (Lovley et al. 1991, Suzuki et al. 2002, Cheng et al. 2012).

As such, while research and development is needed to better understand the effects of microbes in the repository at large, no research specific to the waste form is required. The NWMO will continue to monitor the available literature on these effects.

4.9 Gas Sources and Effects

Gas atoms are produced in the fuel by fission reactions that take place in the nuclear reactor (notably argon and krypton) and by alpha decay in the post-discharge period (helium). The initial fission gases are dominant until about 30,000 years when the cumulative amount of helium from alpha decay would approximately equal that of the fission gases. After one million years, fuel with a burnup of 280 MWh/kgU would contain about $1.7x10^{19}$ He/gU (Tait et al. 2000). As noted in Section 4.6, some of this gas is expected to be retained as interstitial atoms or bubbles with the fuel, but for safety assessment purposes it is assumed that it is released from the fuel and no credit is taken for the long-term integrity of the fuel sheath.

Even if the fuel did release this He gas, there would only be a small increment in pressure inside the container.

Hydrogen gas can be generated through radiolysis and chemical reactions by steel corrosion if water contacts the fuel. In an intact container, the amount of residual water is very small (and likely negligible) because the bundles are dry when placed in the container. As such, only small amounts of hydrogen could be produced, and this would remain in the container (or react with the metals inside the container) unless the container is breached. For a failed container, the introduction of water will result in hydrogen generation by corrosion of the carbon steel as well as by radiolysis close to the fuel surface. This hydrogen gas is expected to produce reducing conditions that would tend to suppress corrosion and dissolution of the used fuel (Shoesmith 2008).

In the postclosure safety assessment, it is assumed that the used fuel is initially (i.e., at the time of placement) in a highly fragmented state with conservative values adopted for instant release fractions. The effects of gas potentially damaging the fuel is already implicitly accounted for and further research in this area is not required.

Research is continuing; however, on the potential benefits of H_2 on fuel corrosion, as noted in Section 4.2.

4.10 Research Program Summary

The information presented in this section shows that for most of the topic areas there are no issues potentially affecting the durability of used CANDU fuel that require further research. This is due to the current state of knowledge, conservative assumptions adopted in the postclosure safety assessment, and sensitivity studies that illustrate low dose consequence for reasonable variations in key associated parameters. No further work is planned in these topic areas beyond monitoring of the literature.

For the topics Used Fuel Dissolution and Solubility, there is currently active research, and it is expected that some research will continue for the foreseeable future.

For non-CANDU fuel types, considerable uncertainty exists. Although there is only a small amount of this fuel; the path forward is not currently decided, and this will evolve further in the coming years as more information about the fuel characteristics becomes available through current programs.

<u>Site Selection and Characterization Phase</u>

Research into improving the mechanistic understanding of used fuel dissolution will continue with NWMO support. Current work at University of Western Ontario is concentrated on the decomposition kinetics of H_2O_2, on the mechanisms of H_2 interactions with UO_2 surfaces in the presence of radiation, and on enhancement of the fuel corrosion model. Future work will consider the specific groundwater chemistry at the candidate sites as that information becomes available.

Regarding solubility, the NWMO will continue to support development of the NEA Thermodynamic Database. Support for work to better define thermodynamic data for higher temperatures and high salinity, currently based at University of Guelph, will also continue, as will efforts to select a thermodynamic dataset appropriate for high salinity conditions.

Work to improve understanding of the behaviour of non-CANDU fuel will also be underway in this phase; however, the specifics of these activities cannot yet be defined.

The broader literature on radionuclide release will continue to be monitored. Tests with used fuel will be considered to improve confidence, particularly if there is an opportunity to share costs with other projects.

Site Preparation and Construction Phase

By this time, it will be known which rock types the repository will be situated in, and research can focus on issues (e.g. site specific groundwater chemistry) associated with this rock.

It is expected that a broad research program will continue through this phase on further improving our understanding of mechanism involved with fuel dissolution and near-field chemistry.

Work to improve the understanding of the behaviour of non-CANDU fuel is also envisaged to continue.

Operations, Monitoring and Closure Phase

It is expected that a broad research program will continue through this phase on further improving our understanding of mechanism involved with fuel dissolution and near-field chemistry.

Major Facilities

No major facilities have been identified for furthering the study of waste form durability.

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5 CONTAINER DURABILITY

The used fuel container is a key engineered barrier in the APM repository conceptual design.

This section discusses the need for research directed towards furthering understanding of the factors and processes that affect the durability of the container, and in particular might cause it to leak and allow water to enter and radionuclides to leave. The factors and processes considered here are discussed in terms of the following topic areas:

- Design, Fabrication and Inspection
- Mechanical Behavior
- Thermal Behavior
- Radiation Effects
- Internal Corrosion
- Processes around the Container.

The copper corrosion barrier is discussed separately in Section 6.

5.1 Design, Fabrication and Inspection

The NWMO reference used fuel container design consists of an inner carbon-steel load-bearing vessel, and an outer copper corrosion barrier. The copper coating is well bonded to the underlying steel container and therefore does not need to be load-bearing. This is illustrated in Figure 5-1.

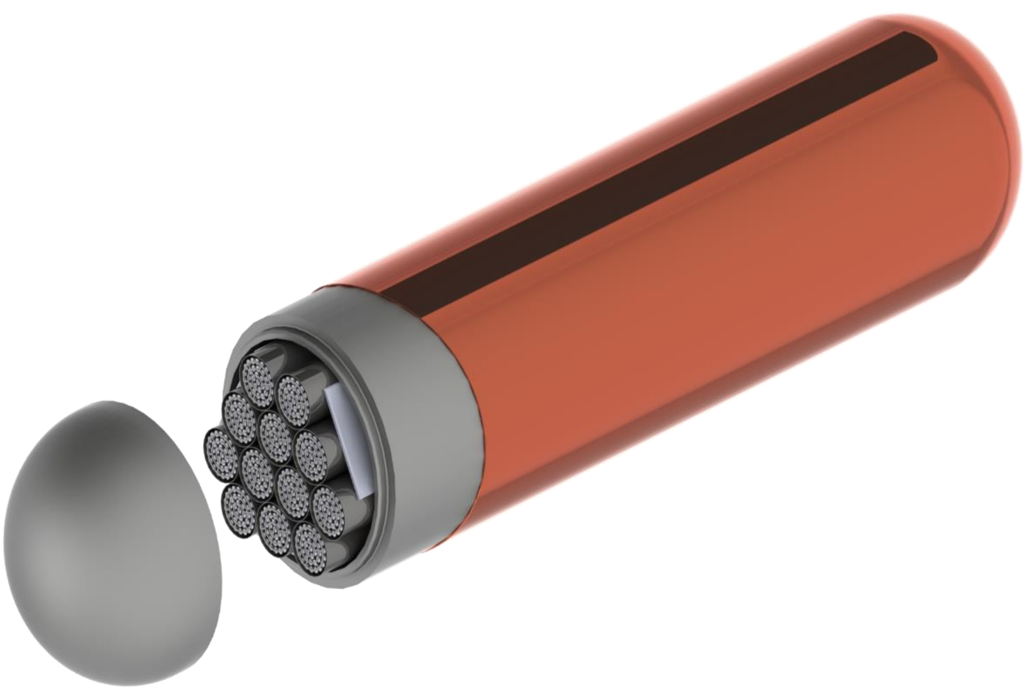

Figure 5-1: Copper Used-Fuel Container holding 48 fuel bundles in four arrays.

For comparison, SKB (Sweden) and Posiva (Finland) also have copper container designs. These container designs have 50 mm-thick mechanically-self-supporting copper shells with a cast-iron insert. The copper shell is made of high-purity, oxygen-free, phosphorous-doped (OFP) copper, with phosphorus added to the copper to increase its creep ductility.

NWMO's design / engineering program is focused on developing repository designs including work to advance the design of the used fuel container. The work program will review and assess the container design considering various evaluation factors such as fabrication technology, handling, interface with underground design, and cost.

5.1.1 Detailed Design

The Used Fuel Container (UFC) structural vessel will be constructed of ASME BPVC carbon manganese steel materials (P1 Gr. 2 classification). This includes SA-106 Gr. C pipe material (for the cylindrical shell), SA-516 Gr. 70 plate material (for the hemi-spherical heads) and SFA 5.18 AWS ER70S-6 weld consumables for the hybrid laser arc weld (HLAW) process.

Within the UFC, fuel bundles need to be housed in a prescribed configuration. The UFC Insert is essentially a carbon steel rack to hold 48 bundles in a UFC; it is similar in nature to the Ontario Power Generation "modules" which house the used fuel bundles after they come out of the reactor, during wet storage, dry storage and ultimately transportation to the DGR site.

Mechanical integrity models are being developed using finite element analysis to predict the container response to mechanical loading following emplacement in the repository (Boyle and Meguid, 2017). These models will continue to examine the effects of buffer swelling, hydrostatic loading and glaciation on the container, and incorporate the effects of cyclic loading and aging to assess lifetime damage to support container licensing. Future work, post site selection, will include design optimization, based on site specific information and the input from long-term experiments, including the Underground Demonstration Facility (UDF) and from international experience.

5.1.2 Container Fabrication and Inspection

Plans for fabrication and inspection, and their development, are addressed in the NWMO proof testing program. This program will include fabrication of 20 containers over the period of 2018-2022, with the bulk of activities occurring between 2019 and 2021.

The UFC steel body will be produced via conventional tube extrusion, a method that will also be used for the UFC insert channels. For the UFC, conventional machining will be used to remove millscale and size the vessel, as well as to prepare the ends for welding. The steel heads will be hot pressed from plate; again, this is routine manufacturing. Welding of the steel container body to one head will be accomplished using conventional welding to produce the container lower assembly. The exterior of the container lower assembly and head will be coated using electrodeposition; these parts will be inspected using ultrasonic and eddy current methods. These are standard industrial processes.

After the container lower assembly is filled with used fuel in the used fuel packing plant during operations, the head will be attached via hybrid laser arc welding (HLAW), a single pass process that does not require post weld heat treatment. Machining of the weld cap and ultrasonic inspection will follow. The coating will be completed over the weld zone using cold spray. As done for the weld inspection, the coating will also be inspected using ultrasonic and eddy current methods. For this application these methods will require some investigation to ensure that suitable equipment is available for the radioactive hot cell. Specifically, the equipment will have to be durable under the radiation emitting through the container wall. Future work will include determining ultrasonic and eddy current probe performance and equipment life in this environment.

Both coating methods are detailed in Section 6.1.

During site selection and site characterization, the primary effort for the UFC steel components will be to streamline fabrication to contribute to mass production. Of primary significance will be the surface finish, post-machining, as this will impact subsequent activities with respect to applying the copper coating. Development of procedures will combine activities for developing quality assurance protocols and for pre-qualification of production facilities.

In addition, UFC inserts will be produced. Along with the 48 bundle UFC insert that will house intact fuel, a modified design will be developed to contain damaged bundles that have been overpacked by the utilities via the Defective Fuel Canning method that is currently under development.

Also during site selection and site characterization (i.e. pre-licensing), the HLAW program will be optimized and demonstrated from small-scale, through pilot-scale operations. For the HLAW, efforts will continue to optimize a low hardness intact weld, which can be applied in a single pass, and without post-weld heat treatment. As a contingency to this reference weld concept, parallel efforts will continue developing and/or monitoring other weld methods, ranging from conventional arc-weld methods to friction stir welding. Should it become apparent that another weld technology is superior to HLAW, the alternative method will be adopted.

During the DGR construction and operational periods, production of UFCs will be critical to the program success; thus, new developments possibly in additive manufacturing or coating methods will be monitored and if appropriate incorporated into the operations. Optimizing inspection methods will also continue through siting, construction, and into operations.

5.2 Mechanical Behavior

5.2.1.1 Deformation

The container is the primary load-bearing structure protecting the used fuel. The basic strength requirements are to meet the normal, seismic and glacial loading conditions, as per the design requirements. The container geometry and steel thickness have been selected for this purpose. Preliminary tests on a full-scale coated and an uncoated container have been conducted, which have verified the onset of deformation to be as predicted from mechanical analyses, and meeting the design specifications. These tests include hydrostatic testing of full-scale prototype containers to pressures beyond the expected pressures and up to failure (Crowe et al. 2016). Up to 3 additional full-scale container tests are planned as part of the proof test program.

Owing to the shape of the UFC (hemispherical ends, cylindrical body), the forces it will be subjected to will be generally compressive from normal and glaciation loads, and will be nearly uniformly compressive at complete saturation/loading. During the early period of the DGR, water ingress into the backfilled emplacement rooms may not be uniform. The resulting differential swelling of the buffer could produce small non-uniform forces on the UFCs, which may even displace them; however, only a small tensile condition will exist.

It is not expected that significant seismic events will occur during the service life of the container, as the site will be located in a region of low seismic activity. However, the effects of shear forces on the container, perhaps produced by highly unlikely seismic processes, will be investigated as a possible postclosure upset condition. The ductile nature of the container provides confidence that minor displacement effects will not cause failure; however, it will be important to quantify the effects on the container. This work will consider modelling of the emplacement room as a whole, as seismic events would affect the sealing system as well as the container. These modelling efforts will be supported by experiments that will combine mechanical and degradation tests; specifically, tests will expose coupons that are bent, elongated or otherwise deformed to conditions that may cause material degradation, primarily through corrosion.

5.2.1.2 Creep Behaviour

The long-term integrity of the carbon steel container has been evaluated with respect to creep. Creep analysis for the steel concluded that the postulated loads will produce a creep strain of ~$6x10^{-6}$ % after the container has been in the repository for 10^6 years (Dutton 2006). Creep is, therefore, not anticipated to have a significant effect on the long term integrity of the steel used fuel containers. No further work on creep of the steel vessel is planned; although this topic will be monitored and a state-of-science review will be developed prior to licensing.

5.2.1.3 Coating Delamination

The coating is bonded to the steel container. This tight bonding ensures that the coating is fully mechanically supported, and also that the coating fully protects the steel. Defective coatings will potentially expose the UFC steel to the environment, and may lead to a galvanic couple. During this process, it is possible that iron oxides will accumulate at the copper-steel interface, a process that could further weaken the coating adhesion.

The fabrication and inspection process will ensure that the as-fabricated containers are bonded. However the possibility of delamination during service needs to be considered. In particular, while the containers will be under compressive stresses once the emplacement room is saturated, there may be differential stresses during the initial saturation period. As a result of the simulations of these scenarios, which demonstrate a maximum delaminating force of ~8 MPa, a minimum adhesive strength of 20 MPa has been defined for copper to steel. Routine tests to date show delamination does not occur until above 60 MPa for both reference cold spray and electrodeposited coatings (Jakupi 2015).

The engineering proof testing program will continue to improve fabrication and inspection to ensure initial well-bonded conditions. However the behavior of delaminated or defective coatings will be studied through ongoing investigation, which will extend into the site-characterization phase, to quantify the extent of this sort of damage. Through site construction, defective coatings will continue to be exposed to repository-like conditions, including in the UDF or other underground facilities, as well as within other research facilities. These samples will be used to validate corrosion models for defective coatings.

5.3 Thermal Behavior

The container surface temperature is held to a maximum of 100°C as a design specification. This is achieved through balancing of the fuel loading, and the container and buffer spacing in the DGR. Various calculations of the container temperature for various repository layouts have established that this temperature limit can be met (e.g. Guo 2016, 2018). Also that the peak temperature occurs on time frames of about 30 years, and then there is a slow decrease in temperature to ambient levels within about 100,000 years.

The corresponding temperatures within the container are expected to peak at about 130°C (occurring within the fuel) within 10-30 years after emplacement underground (Guo 2015).

Comparisons of thermal models with various international heated container concepts have indicated that the temperatures of the containers can be reasonably accurately modelled. During its site selection and characterization phase, the NWMO will continue to participate in projects where it can validate its thermal models, such as DECOVALEX. Eventually the thermal models will be compared with actual performance as part of underground demonstration and performance monitoring at the site.

5.4 Radiation Effects

The container is exposed to gamma and neutron radiation from the used fuel. The gamma dose rate at the outer surface of a container will be up to about 2-3 Gy/h, depending on the fuel burnup and age, while the internal dose rate will be between 25 and 50 Gy/h (Noronha 2016, App B; Morco et al. 2017). Over 1 million years, taking into account the decay of the gamma field with time (see Figure 4-2), the gamma dose to the container interior surface would be about 30 MGy. Calculations for the SKB container indicate about 10^{-7} dpa from gamma irradiation over 0.1 Ma (Guinan 2001). At this level, there would be no significant gamma radiation damage to the container (Farrell et al. 1994, Guinan 2001, Wu et al. 2019).

The neutron flux at the container surface decreases from about $2x10^6$ n/(m^2·s) for 30 year fuel to $1.5x10^4$ n/(m^2·s) for one million year old fuel (Tait et al. 2000). The neutron flux is predominantly fast neutrons with E > 0.3 MeV. Over a one million year time frame, the total neutron fluence experienced by the container material would be less than 10^{19} n/m^2 (about 10^{-6} dpa) (Wu et al. 2019). Defect formation from fast neutrons requires a fluence of about 10^{20} n/m^2 in copper and iron at 70-80^{o}C to cause measurable hardening (Fabritsiev and Pokrovsky 2002, Eldrup et al. 2002).

Consequently, the container steel and copper components are not expected to undergo direct damage via radiation, as damage thresholds are several orders of magnitude greater than will be produced by the used fuel. However, it is possible that radiation may produce species that can cause corrosion both inside and outside of the UFC. These concepts are described in Section 5.5 and Section 6.2.2, respectively.

5.4.1 Hydrogen Embrittlement

The container metal could embrittle due to interaction with hydrogen produced by radiolysis within or outside of the container. Owing to the (comparatively) low dose rate of radiation and the absence of sufficient quantities of chemical precursors inside the sealed UFC (water, air), the amount of hydrogen produced inside the UFC is several orders of magnitude below that required to cause embrittlement of steel (Wu et al. 2019). Similarly, the exterior copper coating will be exposed to only very small amounts of hydrogen through interactions with sulphide/water, and these will be insufficient to embrittle copper.

Although the hydrogen presence at both the steel and copper surfaces is expected to be extremely low, trace quantities may enter either metal. Should the hydrogen reach the steel-copper interface, it is possible that its solubility will be exceeded while it crosses the interface; a blister/bubble of hydrogen would result. Ongoing work is exploring this concept, despite an absence of evidence of blistering for the copper-steel interface. This work will be concluded during the site selection and site characterization phases.

5.5 Internal Corrosion

An assessment of internal corrosion mechanisms was completed (Wu et al. 2019). The assessment included general corrosion, localized corrosion, stress corrosion, hydrogen effects and radiation embrittlement.

The UFC will be filled with used fuel bundles and sealed in an air atmosphere. Moisture will be present due to the air humidity and through small amounts that are retained on or within the fuel bundles. This should be very low, as most fuel bundles will have been in dry storage for some time, and certainly will be under dry conditions for transportation to the site. Despite long-term dry storage, the possibility of undetected defects within the fuel cladding during wet storage could result in the presence of some water within the UFC.

Water and air trapped inside a UFC will cause corrosion, a process that will be complicated by the emission of radiation from the spent fuel. Owing to the limited amount of water and air, general corrosion cannot cause failure; only a few micrometres of damage would occur. In addition, it has been experimentally demonstrated that damage will not be localized within the weld zone (Wu et al. 2017); instead corrosion occurs on the exposed face of the steel. Additional experiments are ongoing on weld zones, including those exposed to gamma radiation fields in various environments (humid air, in solution), and at a range of temperatures.

Although localized corrosion such as pitting is not expected and has not been observed during experiments, the need remains to develop an internal corrosion allowance. The nature of the oxide formed on the steel surface may vary from conductive to highly insulating, resulting in a distribution of general corrosion rates, leading to slight surface roughening. In addition, species such as nitric acid may be produced and condense as droplets, with the corrosion they cause leading to further roughening of the surface of the steel. Some effort will be required to assess the possibility of corrosion due to galvanic couples that exist within the container: spent fuel and zircaloy; zircaloy and carbon steel; and in the case of overpacked damaged fuel bundles, stainless steel and carbon steel.

Within all of this work, it will be necessary to consider the ongoing changes to the internal atmosphere. Oxygen and water vapour will be consumed during corrosion and anoxic corrosion will produce hydrogen during the period immediately after closure of the container. Over the long service life, helium will be produced as a result of radioactive decay of the actinides in the fuel, and will eventually be the dominant gaseous species. The internal pressure may rise to a little under 0.5 MPa over one million years, which is well within the tolerance of the vessel; an external pressure as high as 8 MPa from bentonite swelling will also overwhelm the effects of the internal pressure. Regardless, it will be necessary to confirm that trace species that could potentially be released from the fuel matrix (i.e. iodine) are unable to initiate cracking under the conditions expected inside a UFC. To address this consideration, the ongoing experimental program will be augmented to include longer exposures to radiation in environments that contain possible cracking agents that may be released by the fuel. To accelerate effects, some coupons will be plastically deformed prior to exposure.

Significant research efforts will be required during the period of site selection and site characterization; although the site condition is not highly relevant to the outcome of internal container processes. A significant outcome of this effort will be a corrosion model that will incorporate the experimental data, will account for all internal processes affecting corrosion, and will produce a corrosion allowance. Over time, this modelling effort will need to be extended to include any additional used fuel types developed by the Canadian industry, as well as to account for any site-specific conditions (e.g. changes to expected external pressure) or operational changes (e.g. improvements to the understanding of the hot cell operations/atmosphere) that may be required in practice.

5.6 Processes Around the Container

During emplacement, the container will be exposed to a continuing, slow ingress of water through the bentonite sealing system. The water chemistry will be impacted by both the consituents of the bentonite, as well as the geochemistry of the surrounding rock and any microbial activity within the surrounding rock or the excavation damaged zone (EDZ). While the water chemistry will impact any potential corrosion processes affecting the copper (Section 6.2), it will also contribute to the swelling pressure of the bentonite, which decreases as the salinity of the water increases. In addition to the mechanical forces that the swelling bentonite will impart on the container, the bentonite will heat as a result of the radioactive decay of the fuel, and these effects will propagate among the many containers in an emplacement room.

To adequately quantify the combined effects of thermal, hydraulic and mechanical (THM) processes, it will be necessary to perform a combination of both experimental and modelling programs. For modelling, two primary codes have been identified: COMSOL and CODEBRIGHT, both of which model the effects of the multiple physical processes that occur, and are described in Section 7.5.3. To complement these models, some selective experiments will be conducted, during which data will be obtained for temperature, pressure and mechanical impacts of the ingress of water into the emplacement room. A series of scaled experiments will be performed, as described in Section 8.6.2.

The NWMO has also participated in, or observed, various container tests and the corresponding interactions between the container and the external buffer and rock. Example tests include the Buffer-Container Experiment (BCE) in Canada, and the Prototype Repository, FEBEX and FE heated container tests in Europe. The containers in these tests are not specific to the NWMO, but these tests help confirm the conditions under which containers will operate in an actual repository. The NWMO anticipates that prototype tests will be conducted within the UDF at its site, and it will also conduct performance monitoring of actual emplaced containers. The details of these tests have not been determined.

5.7 Research Program Summary

The information presented in this section illustrates that the container concept is based on sound engineering practices, in that the design decisions were made to minimize the potential degradation processes that may affect container durability. Specifically, the container is free of complex features/welds/gaps that may present future problems; thus, the mechanical performance is not difficult to predict for the as-fabricated container. Environmental perturbations such as radiation and thermal inputs are small and unlikely to affect the metallic components. However, owing to the long service life, the research program is wide-ranging, and is mindful of synergistic effects that may affect performance. One additional consideration is the long-term nature of the fabrication program that will accompany the operations phase of the DGR program, as it is likely that improvements to individual fabrication steps will be made (i.e. enhancements in weld technology/quality through a future technology shift). As a result, it is expected that programs will continue for the foreseeable future on this topic. Programs specific to copper are described in Section 6.

Site Selection and Characterization Phase

The broad research program will continue, to further the understanding of the degradation of the container components. The effects of radiation, temperature and pressure on steel and welded steel corrosion will be covered within this topic, to ensure there are no unresolved issues at licensing. As noted above, consideration will be given for the presence of the fuel, cladding and any other components that may be contained.

Prior to licensing, it will be necessary to finalize the container design, including identifying reference fabrication processes for steel and copper components and container welding/inspection and handling processes. While these activites are a function of engineering, degradation/corrosion testing will be required to ensure that the service life can be achieved.

In addition, prior to submission of a safety assessment report, it will be necessary to develop a detailed description for all the internal processes that may occur over the course of the repository life. As additional information regarding defective fuel overpacking and possible new waste types are included, effects on the internal environment will have to be updated to ensure that container integrity will not be compromised. Some long-term experiments will be initiated to support operation license activities.

Site Preparation and Construction Phase

The broad research program will continue on the internal processes affecting container integrity, and new information will be incorporated into the site-specific safety assessments. As container fabrication programs become more comprehensive, an ongoing stock-taking of the program results will occur, and additional experimental programs will be initiated as necessary.
Some long-term experiments will be disassembled and analysed, as samples become available.

Operations, Monitoring and Closure Phase

As noted above, the broad research program will continue to explore the fundamental processes affecting steel corrosion as a function of the internal environment.

As early as possible, scaled or full size containers will be placed into the Underground Demonstration Facility to obtain site-specific performance data, in support of the existing data. This will commence the long-term activity of demonstrating operations and developing data to support durability. Samples will be periodically retrieved / replaced to allow for characterization over the course of operations. During monitoring and closure, this program will wind down.

Major Facilities

No new specific major facilities are required prior to construction. Many of the programs listed above will occur in University and National Laboratory environments, throughout all project phases. The primary facility required during construction is the UDF.

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6 COPPER DURABILITY

The corrosion barrier in the used fuel container (UFC) is the copper outer layer. It is applied as a coating in the reference container design. The durability of this copper layer is key to the long-term container durability. The factors and processes considered here are discussed in terms of the following topic areas:

- Fabrication and Inspection
- Copper Corrosion
- Mechanical Behavior
- Radiation Effects
- Interaction with the Surrounding Buffer

As these topics are interrelated, as well as connected with geological processes and container design, detailed descriptions are presented in this section and elsewhere in this document.

6.1 Fabrication and Inspection

As described in Section 5, the UFC requires an integrally bonded copper coating to function within the DGR. Two methods for applying the coating have been selected and extensively reported on (Choi et al. 2010; Keech et al. 2014; Standish et al. 2015; Vo et al. 2015, Jakupi et al. 2016; Giallonardo et al. 2017): electroplating for components coated prior to fuel loading, and cold spray coating for the weld closure zone after fuel loading. The former method takes advantage of extensive commercialization and low cost, despite being a relatively slow process, while the latter has the benefit of being a rapid process that does not require liquid media, thereby simplifying the hot cell operations required for its application. All coatings will be inspected using ultrasonic and eddy current methods to verify their integrity. Fabrication and inspection is further addressed in the NWMO proof testing program.

Optimization of the electrodeposition bath chemistry and plating parameters will continue during site selection and site characterization, to ensure that high quality coatings can be produced reliably on a pilot scale production basis. During DGR construction, the electrodeposited copper coating will be further optimized to maximize production efficiency; these activities will occur off-site, eventually moving to a dedicated container manufacturing facility, which will operate throughout the DGR lifespan. This task will combine two activities: (i) development of quality assurance protocols and (ii) pre-qualification of production sites should they be off-site of the DGR.

Regarding the cold spray technique, important variables such as powder purity and size, thermal properties and gas composition will be varied during the pilot scale production stage, and continuously improved during the subsequent site characterization and DGR construction time frame, to repeatably produce high quality coatings. Ongoing work on laser assisted cold spray procedures will continue to explore whether coatings may be heat-treated *in situ* to enhance coating ductility rather than after coatings are completely applied. Lasers will also be investigated as a means to eliminate the use of helium as the carrier gas, since their use shows promise to reduce the reliance of the cold spray process on a finite and expensive natural resource.

For both copper coatings, it is critical to define copper purity requirements suitable for the manufacturing programs. This is essential since potential contaminants may be incorporated during both coating processes, and could alter the performance of copper, and particularly its corrosion performance. Activities in this research area are described in Section 7.2, and must take place during the present pilot scale production stage, as well as during construction, while manufacturing lines are optimized.

During the DGR operational period, production of UFCs will be critical to the program success. Relevant new developments such as in additive manufacturing related to copper coating and inspection of coatings, will be incorporated into operations.

6.2 Copper Corrosion

There are a number of processes by which copper can possibly corrode during its service life in the DGR (Scully et al. 2016; Scully and Edwards 2013; Hall and Keech 2017). These are:

- Oxic corrosion during the handling and early emplacement period;
- Radiolysis induced corrosion during the early emplacement period;
- Corrosion during the subsequent anoxic period through interaction with anionic groundwater species such as chloride, sulphide or carbonate/bicarbonate;
- Microbially-induced corrosion;
- Galvanic corrosion;
- Stress corrosion cracking;
- Mechanical enhanced of corrosion and corrosion reduced mechanical performance, including weakening of copper via embrittlement.

For each of these processes, specific mechanistic and morphological impacts must be considered, since corrosion damange can be unevently distributed, depending on exposure conditions. A knowledge of this distribution is essential for a corrosion allowance to be reliably specified. Of particular note are potentially highly damaging processes, notably stress corrosion cracking (SCC) and corrosion under biofilms. While neither of these are anticipated on copper in the DGR, this must be demonstrated.

6.2.1 Oxic Corrosion and Oxic Pitting

Oxygen present in the DGR from air, introduced during emplacement and trapped on sealing is expected to cause corrosion, which, in principle, can occur uniformly or at local features. Using mass balance arguments, the maximum total damage expected for general (uniform) corrosion due to trapped oxygen is readily calculated to be approximately 80 µm, depending on the exact geometry of the DGR and the geology (Hall et. al. 2018). As the damage due to general oxic corrosion will be small, the only significant oxygen damage will be limited to the period over which it could sustain localized corrosion via the separation of anode and cathode locations (King et al. 2010).

In the experimental program on pitting, the conditions under which copper is able to actively corrode (i.e. localized corrosion is not possible) or will passivate (i.e. localized corrosion is possible) are being investigated using the standard electrochemical approach of recording potentiodynamic polarization profiles. From the potentiodynamic data, the active/passive conditions for a range of solutions that contain one, two, or three anion species have been established. For example, the active/passive boundary for solutions prepared with various chloride concentrations at various pH values have been determined (Qin et. al. 2017).

At the expected DGR pH, all concentrations of chloride demonstrate active conditions. In general for chloride dominated solutions, passive conditions can only occur at very elevated pH values (i.e. > 10). Increased temperatures and chloride concentration further elevate the pH required to establish passive conditions (i.e. > 11). High pH conditions are not expected within the DGR environment, and therefore pitting is not expected to be significant should chloride be the dominant anionic species. However, where carbonate/bicarbonate or sulphate species are considered, the active-passive boundary shifts to lower pH, especially when the chloride concentration is low. Although DGR conditions still appear to be within the active region, the pH margin is reduced, and it remains unclear how much margin remains before the system switches to passive conditions.

Future work will continue to further the understanding of any localized corrosion effects. Of specific interest is a prediction of oxic damage that may occur during the unsaturated period, as this is a likely scenario for the DGR: in fact, oxygen is likely to be depleted prior to full saturation, the condition at which previous predictions have been made. The work will include the development of a model to simulate the corrosion potential within the DGR. For both saturated or unsaturated conditions, an improved statistical treatment is required to develop a more complete life-cycle probabilistic pitting model. This is the usual mathematical analysis used for systems where pitting is expected, to predict the probability of pitting and of repassivation, and to estimate pitting depths. To this analysis, a time-dependent probability for the environmental conditions that permit pitting will be added to the assessment, such that the total probabilistic analysis will produce a complete statistical assessment of pitting under DGR conditions.

In the absence of classical pitting, it is still necessary to assess the surface roughening that may occur for copper during nominally "uniform corrosion". In general, roughening or 3-D texturing of a surface may occur during both metal loss (i.e. corrosion, Kwong 2011) and metal gain (i.e. electrodeposition/electroplating) events, producing a non-smooth surface. Within the DGR environment, it is understood that some roughening will occur (Kwong 2011). To further this understanding additional experiments will be conducted over a range of time periods, to verify that roughening does not exceed a few tens of microns(Kwong 2011). In addition, unsaturated experiments will be performed, during which the humidity is near the dewpoint. Such conditions, particularly in the presence of salt crystals on the copper surface, will produce water droplets, within which localized corrosion could occur. Previous experiments in this area did not demonstrate any significant localized corrosion effects(Ibrahim et al. 2018). However, the studies were also focused on the effects of radiation, and only lasted a few months (Ibrahim et al. 2018).

During the course of site selection and characterization, this research program will include both laboratory and field studies. Laboratory tests will investigate the influence of actual site specific groundwater chemistry, as well as temperature and pH, and collect systematic data to support a general process understanding. Field tests will involve emplacement of specimens in borehole modules in various environments, ranging from URLs in other countries to borehole modules in Canadian locations. In general, the purpose of the field studies is to confirm observations made within the well-defined conditions from laboratory studies, since field studies offer less experimental control. For URL studies, oxygen trapped immediately after emplacement may produce damage that is quantifiable. In addition, experiments conducted in DGR analogues, such as deep ocean locations, are likely to contain trace amounts of oxygen that would be expected to produce a known amount of corrosion damage. Whether this is the case will be assessed by comparing expected to observed damage.

During the construction phase, these analyses will be augmented with experiments conducted in the UDF, which will allow for the site-specific assessment of the effect of entrapped oxygen, as current calculations presume very conservative assumptions with respect to oxygen consumption. Subsequent operational experience during both construction and operations will augment the calculation of mass balances for oxygen, as institutional knowledge of DGR construction/dimension and bentonite fabrication methods will improve the calculation accuracy.

6.2.2 Corrosion via Radiolysis

Prior to the adoption of the copper coated UFC, only very small dose rates of radiation from fuel decay were expected to penetrate the thick container walls. With the adoption of the new design, a more significant radiation field will be present, potentially on the order of 1-3 Gy/hr initially (Morco et al. 2017). As a result, the concern has been raised that some radiolysis of water within the environment surrounding the UFC will produce oxidizing species such as hydrogen peroxide, which may lead to container corrosion. The goals of this program are to refine the understanding of the long-term performance of copper in radiation environments, to identify whether there is a possibility of increased corrosion, and to assign a corrosion allowance for radiation-related processes, if applicable.

To date, a refined analysis of the radiation dose and a preliminary calculation of the concentrations of the resulting radiolytic species has been performed for the UFC in wet oxic aerated conditions. In addition, a conceptual model for radiolysis in humid air has been developed; this analysis includes both water and nitrogen chemistry, from which a preliminary damage assessment of nitric acid droplets have been derived (Turnbull et al. 2017; Morco et al. 2017). Finally, the effect of very high chloride, including its direct interaction with radiation in the aqueous environment has been assessed, and early validation work has been completed.

However, within the aqueous-radiation environment, questions remain about the mechanism of corrosion of copper, including its oxidation state, dissolution and precipitation steps that may comprise the process. In addition, the current understanding of copper corrosion kinetics under irradiation cannot satisfactorily explain the observations in the different studies presented in the literature. A more systematic investigation of these systems is of vital importance for copper corrosion modelling. Key parameters include pH, dissolved O_2 concentration, water volume to copper surface area, the effects of copper complexing anions, radiolytic oxidant concentration, and exposure duration. The goal of such a study is to provide sufficient insight to include an accurate radiolysis component in the copper corrosion allowance. The experimental program will include a range of gamma dose rates, from below DGR conditions to orders of magnitude above, to help model the effect of the diminishing dose rate over the very long time period required.

This effort will continue over a prolonged period that includes site selection, DGR construction and operations, as the understanding of the radiolysis process is continually refined. While much of the work will need to take place in controlled laboratory environments, specific experiments involving the UDF during construction/operations may include tests with gamma sources (e.g. Co-60 or monitored used fuel UFCs), such that radiolysis processes can be directly assessed following container emplacement.

6.2.3 Anoxic Corrosion

The long term stability of copper in water in the absence of oxygen has been extensively investigated for many years. The basic process can be considered an equilibrium between copper and water, and cuprous oxide and hydrogen, Equation 6-1.

$$Cu_{(s)} + H_2O \rightleftarrows Cu_2O + \frac{1}{2}H_{2\,(g)}$$

Equation 6-1

Thermodynamic calculations indicate that this reaction is heavily shifted to the left, such that a partial pressure of only 10^{-16} bar of hydrogen would suppress oxidation of copper (King and Lilja 2011). This thermodynamic balance provides the justification for the selection of cooper for the corrosion barrier of the UFC.

6.2.3.1 Pure Water Effects

A proposed variation of the copper-water equilibrium, whereby copper is reactive with water (Equation 6-2) has received considerable debate since it was reported in the 1980s. The initial observations included a larger than expected quantity of hydrogen produced during exposures. This was attributed to the production of an adsorbed cuprous hydroxide.

$$Cu_{(s)} + H_2O \rightleftarrows "CuOH_{\,(ads)}" + \frac{1}{2}H_{2(g)}$$

Equation 6-2

Despite the lack of thermodynamic evidence for a “CuOH” product and an independent verification of the amounts of hydrogen detected, the presence of such a corrosion mechanism must be verified and quantified or invalidated. Other experiments, including work by NWMO with very precise hydrogen monitoring, have generated only very small amounts of hydrogen indicating that this will not be an important process in repositories (Senior et al. 2013, 2019).

Further work is planned involving very long term exposures, during which copper will be immersed in pure water, and headspace gases in the reaction vessel will be analysed for the presence of hydrogen. In addition, surface analyses will be performed at the conclusion of multiyear experiments, to identify any corrosion products that may exist. Solutions will be examined for the presence of dissolved copper species, including colloidal species.

One possible complication is the amount of hydrogen trapped in copper during manufacturing. While the amount is small in absolute terms, it may be sufficient to complicate the interpretation of experiments involving low production rates of H_2 that might be associated with Equation 6-2. Significant variability is observed for different copper product forms, and annealing of copper prior to exposure has been proven to dramatically reduce hydrogen release during exposure experiments (Hedin et al. 2018).

6.2.3.2 Chloride Effects

Copper is anticipated to corrode slightly more in anoxic, high salinity environments via Equation 6-3; although trace amounts of hydrogen are still expected to suppress this equilibrium. Previous work by the NWMO has measured transient hydrogen production rates that correspond to corrosion rates of a few nm/year in chloride-containing solutions at elevated temperatures (i.e. 75°C). In most cases, the measurements of hydrogen diminish with time; however, given that potential host sites for the DGR are expected to be chloride dominated, the effect of chloride concentration on the anoxic corrosion of copper must be better understood and appropriately quantified for Canadian disposal conditions.

$$Cu_{(s)} + H_2O + nCl^- \rightleftarrows [CuCl_n]^{(n-1)-}_{(aq)} + \frac{1}{2}H_{2(g)} + OH^-$$

Equation 6-3

6.2.3.3 Anoxic Corrosion via Microbially Influenced Processes

Sulphide is expected to be the greatest contributor to copper corrosion throughout the lifetime of the UFC. While the groundwater at potential Canadian repository sites will likely contain little to no sulphide, it is possible that microorganisms could produce sulphide by the biological reduction of sulphate. Sulphate will be present in the groundwater at low levels, and may be present in the bentonite buffer. Therefore Microbially-Influenced Corrosion (MIC) is a key long-term corrosion mechanism relevant to the UFC service lifetime.

As discussed in Section 7.8, the dense bentonite around the UFC will prevent significant microbial activity. Therefore, microbial sulphide production would occur only in the geosphere or at the buffer/geosphere interface. This sulphide would have to diffuse through the bentonite in order to reach the UFC, which will be a slow process. However, once the sulphide reaches the container, corrosion proceeds quickly according to Equation 6-4.

$$2Cu_{(s)} + HS^- + H^+ \rightarrow Cu_2S_{(s)} + H_{2(g)}$$

Equation 6-4

Since copper oxides could be present from the earlier period of oxic and radiolytic corrosion this would create a complex surface film consisting of copper oxides/hydroxides, copper sulphides and exposed copper. While evidence exists to show Cu(I) oxide will be converted to Cu_2S and Cu(II) species are expected to be unstable in the presence of SH^-, the influence of the complex chemistry/electrochemistry on the subsequent distribution of corrosion damage remains to be clarified if a justifiable corrosion allowance is to be specified.

The most current DGR models suggest that the amounts of nitrite, ammonia and acetate produced through other microbial metabolic activity are likely to be very small and would not result in a significant amount of corrosion of the copper containers (K. Pedersen 2000).

6.2.3.4 Other Anionic Species

Further complicating the prediction of the evolution of copper corrosion with time in a DGR is the presence of many chemical species and impurities in groundwater and clay porewaters. The specific groundwater conditions of the DGR site are not currently known. Typical groundwater impurities such as lead or other heavy metals need to be quantified with respect to their effect on anoxic copper corrosion. Additionally, any natural buffer species (i.e. carbonates, phosphates etc.) present in groundwaters and porewaters could have an effect on the mechanisms of copper corrosion by controlling the pH in the DGR and interfering with the reaction with sulphide. In order to fully account for the effect of such species on copper corrosion, each species should be investigated individually and in combination to increase confidence in the NWMO's finally specified copper corrosion allowance.

6.2.3.5 Anoxic Corrosion Work Program

Prior to assessing the amount of hydrogen produced through the interaction of copper and water with or without anionic species, significant effort will be dedicated to quantifying the amount of hydrogen in the copper coatings proposed for the UFC prior to and post exposure. This will require refinement of conventional analyses, such as the LECO test, which is commonly used for materials containing hydrogen (e.g., embrittled steel), but is not generally used to analyze hydrogen in copper. This will remain an active research topic, as hydrogen uptake and analysis is a widespread industrial concern spanning many processes and disciplines (i.e. corrosion, energy storage, fuel cells, metal refining, metallurgy, etc.).

On subsequent exposure of the copper to various solutions from pure water to solutions containing the anionic species listed above (chloride, sulphide, etc.), the hydrogen produced can then be measured against an established baseline hydrogen content. For sulphide exposures, a range of solution compositions which partially or completely cover the copper surface will be explored, with the resultant films being well characterized using surface analysis methods. Focus will be on the nature of the sulphide film, as the formation of porous films will lead to general corrosion, whereas compact dense films have the potential to produce localized or pitting corrosion. To date, it is well established that the expected repository conditions (i.e. dilute sulphide, stagnant aqueous environment) will produce porous films (Martino et al. 2018).

One particularly relevant process that will be explored is the production of sulphide-containing films through gaseous processes. Such a process could occur in a DGR if microbial activity were to initiate during buffer wetting, to produce sulphide that could be transported to the container surface after partitioning as H_2S to the gaseous phase. While such a transient process is not likely to affect container safety, the nature of the copper sulphide film formed has not yet been studied with respect to its ability to passivate the copper surface, and, hence, possibly support pitting.

From these anoxic experiments, it will be possible to refine the copper corrosion allowance to account for the effect of microbially-produced sulphide. These programs will be conducted in concert with the bentonite program, since the suppression of microbial activity near the container is only possible through the use of highly compacted bentonite (HCB). In the immediate viscinity of the container, HCB blocks will be used with densities in excess of 1.7 g/cm^3; where biofilms are not expected to form. However, beyond the HCB, the confidence of microbial suppression is lower in both the gap fill material (GFM), and especially at the bentonite-rock interface. These topics are addressed in Sections 7.8 and 9.3.5 respectively. Output from the programs listed therein will be addressed within the anoxic corrosion program, which defines the copper corrosion rate and the corrosion allowance required.

Since the performance of the UFC relies on the stability of copper within the anoxic aqueous environment of the DGR, it is expected that research in this area will continue through all aspects of the DGR program. Prior to site selection, the work will occur in laboratory environments and within the URLs and other field studies. Since URL studies will involve long exposures, these studies will continue through to licensing and beyond into the DGR construction phase. In addition, for some of the possible siting communities, borehole modules will be located at repository depths for periods of up to 10 years. Within these modules, copper cold spray, electroplated copper and reference high purity copper coupons will be placed in bentonite compacted to different densities. It is expected that the groundwater will gradually travel into the modules, and that the residual oxygen will be quickly consumed. Modules will be removed periodically, disassembled, and the bentonite and container materials examined for degradation.

Following site selection, studies on anoxic corrosion will focus on the effect of groundwater chemistry. During site characterization, laboratory tests will be performed in solutions simulated to correspond to groundwaters extracted from boreholes. Borehole monitoring / testing will continue, and additional information will be obtained to augment the understanding of corrosion. During construction, additional exposure tests will be conducted within the UDF to demonstrate corrosion performance under site-specific conditions.

6.2.4 Stress Corrosion Cracking

In order for Stress Corrosion Cracking (SCC) to occur, it is necessary to have a combination of a susceptible material, a sufficient tensile force, and an environment containing SCC agents which enforce a suitable electrochemical potential. In the absence of any of these conditions, SCC cannot occur.

Owing to the shape of the UFC and the compressive mechanical loads expected from buffer swelling and the hydrostatic head and glaciation loads, the UFC is expected to be under predominantly compressive stresses. During buffer saturation, there is a limited period during which uneven wetting could produce some very small local tensile forces; however, these are far below the threshold for SCC. Therefore sufficient tensile forces associated with SCC cannot be generated at the copper coating within the DGR.

In addition, SCC experiments have been conducted to determine the effect of oxidant, SCC agents (nitrite, ammonia and acetate) and chloride on the SCC behaviour of copper containers in a deep geological repository (Ikeda and Litke 2000). A model has been developed to predict the SCC behaviour of a copper container in a DGR (King and Kolar 2005). The findings from both experiments and modelling indicate there is minimal environmental risk of SCC of copper containers in a deep geological repository since the production and supply of SCC agents to the container surface will be very limited. The limited amount of oxygen in the sealing materials would further restrict the time period that a copper container might be susceptible to SCC. The susceptibility of copper to SCC would also be suppressed by the presence of chloride in the groundwater, as this anionic species promotes general, and not localized, corrosion.

Although NWMO is confident of the ability of the DGR to avoid conditions leading to SCC, some work is underway to improve the fundamental understanding of SCC conditions. Specifically, the empirical observations regarding chloride suppression of SCC, even where suitable tensile forces and SCC agents are utilized (Ikeda and Litke 2007, 2008; Litke and Ikeda 2008; 2011), require further mechanistic analysis to provide more confidence in these predictions. Specific work will include high resolution characterization of cracked samples, including a systematic study to assess conditions that produce crack blunting. This work is expected to proceed at a relatively slow rate through site selection and characterization phases of the program within laboratory environments. During construction and operation, this topic will continue to be investigated through academic collaborations that involve further mechanistic studies, likely on related metals.

6.3 Interaction of Copper with Buffer

The NWMO has extensive research programs focused on copper corrosion, bentonite properties and microbiologically influenced corrosion (MIC). However, less work has focused on copper-bentonite interactions or their implications for copper corrosion, bentonite properties or microbial behaviour. Furthermore, previous microbiological work used to define highly compacted bentonite (HCB) specifications for emplacement dry density has been conducted in predominantly aerobic conditions for relatively short durations (i.e. 90 days) (Stroes-Gascoyne and Hamon 2008; 2010). Therefore, similar microbiological characterization is required in DGR relevant environments (i.e. anaerobic for long timeframes) to demonstrate that current bentonite designs for HCB are sufficient to suppress microbial activity and to define a similar design specification for gap fill material (GFM).

To date, some preliminary work has been conducted in both the Mont Terri and Grimsel URLs. Within this work package, characterization of groundwaters, bentonite and container coupon materials are being performed, with the goal of correlating microbial, physical and geochemical parameters to the corrosion damage observed. Only very early samples have been analyzed; thus time-dependent data is not yet available.

As a further investigative tool, NWMO is developing first-of-a-kind modules to conduct experiments within boreholes drilled during the siting program at repository depth. While conceptual design has been proposed for both the modules and the tools for emplacement and retrieval, this program has not yet advanced to fabrication of equipment.

During site selection and site investigations, cold spray, electrodeposited and wrought copper specimens will be packed in HCB and GFM inside a range of of aerobic and anaerobic pressure cells. Prior to site-selection, generic simulated porewater will be used to saturate the bentonite, and tests will be monitored for up to five years under laboratory conditions. Upon test completion any degradation of the copper or bentonite will be characterized and quantified in parallel with microbial analysis of the copper, bentonite and test apparatus to:

- Improve confidence in the design specification for the emplaced dry density of HCB to prevent microbial activity.
- Support a design specification for the emplaced dry density of GFM to prevent microbial activity.
- Improve confidence in the copper-bentonite engineered barrier systems to suppress copper corrosion.
- Refine and improve confidence in the NWMO’s MIC copper corrosion allowance.

Once available during the siting process, the reference groundwater conditions will be updated and reproduced for laboratory tests, and additional confidence building experiments will be conducted. Throughout both of these periods, experiments will also be conducted within the international URLs, as noted above, to produce time-dependent results. Efforts in both laboratory and international URLs will diminish during construction, as the focus switches to

UDF operations (see below); however, it is expected that ongoing academic expertise will be retained for this topic.

As noted above, experiments to assess bentonite-copper interactions at repository depth are being initiated. These modules will be emplaced during site selection, and periodically removed throughout the site characterization, construction and operation phases. Results from these experiments will be incorporated into design and each phase of licensing and site activities.

Upon the development of the UDF, emplacement of container modules / coupons into representative bentonite installations will be conducted. Like the modules at repository depth, results from these experiments will be incorporated into safety assessments and relevant documentation that will enable the ongoing site activites (construction, operation and site decommissioning).

6.4 Mechanical Behaviour

As noted elsewhere in this document, extensive research to understand bentonite properties and copper corrosion behaviour is underway. Within the DGR, the bentonite will impact the chemical exposure environment of the copper (Section 6.3), and it will also provide significant compressive mechanical forces, a feature that is enhanced by both the hydrostatic head and (in the long term) glaciation (Section 10.1). While the steel is expected to provide container strength and prevent mechanical dislocation of the copper, including creep, some consideration for the potential effect of temperature and pressure on the mechanical performance of copper is necessary.

Initial activity in this research area includes a relatively simplistic analysis of the changes expected to the container that may impact the mechanical behavior of the copper. As copper corrosion is expected to be minimal, it is not expected that hydrogen from corrosion will cause a loss of ductility from embrittlement (Section 5.4.1) or cause delamination of the copper coating from the steel (Section 5.2.1.3). As noted in Section 6.4, tensile forces are not expected; thus, cracking phenomena are not anticipated. Also, tests have confirmed the high adhesion strength of the coating, and mechanical debonding is also not expected.

To augment the assessment of mechanical-corrosion behaviour noted above, failure diagrams will be developed for the copper coated container. For many materials, these are the de facto tools to assess the changes of mechanical properties as a result of corrosion that could result in early failure. The purpose of developing these diagrams will be to quantify the safety margin for the loss of mechanical strength from different corrosion modes, elevated temperature, radiation and a range of environmental conditions. The diagrams will include degradation of neighbouring containers or other repository features (i.e. structural steel), as such processes could lead to sequential container failures.

To supplement the failure diagrams and their ability to resolve the failure boundary conditions, some experimental work will be conducted, during which accelerated degradation conditions and extreme forces (including tensile conditions and cyclic loading) will be explored. Work of this nature is expected to proceed during site selection within controlled laboratory environments, and will include a range of temperatures. The experimental matrix will explore the consequences of mechanical deformation followed by corrosion damage, as well as corrosion damage prior to mechanical testing to assess whether the combined effects on performance are sensitive to the order in which these processes occur. During site characterization and following container production optimization, this topic will be explored for larger components. This will involve efforts to artificially age full size UFC components prior to cyclic pressure testing.

For experiments initiated in the UDF, it will not be possible to observe experiments at full pressure prior to saturation; thus, any mechanical-corrosion assessments will start during construction, but cannot be analyzed until operations are underway. Accordingly, the NWMO will continue to utilize a different analogue to explore corrosion experiments at pressure: immersion of modules containing bentonite and container materials in ocean environments. Using coupons in bentonite at various densities and installations at different depths, pressure and potential for microbial activity can be varied to supplement knowledge on their effects. Initial development of modules and procedures is underway with Ocean Networks Canada, and these experiments will be conducted for durations ranging from months to years.

6.5 Radiation Effects

The copper will be exposed to gamma and neutron radiation levels that are expected to correspond to damage levels of around 10^{-6} dpa over one million years (see Section 5.4). At these levels, radiation effects are not expected in the bulk metal. The NWMO is presently looking at the possibility of examining irradiated copper components from NRU as a further test of the impacts of gamma and neutron irradiation on copper.

6.6 Natural Analogs

Unlike most metals, copper can be found in metallic form in the earth. This property is based on thermodynamics, as copper does not naturally corrode in water in the absence of oxygen. As a result, naturally occurring coppers offer an opportunity to study very long-lived samples, including those that are more than one billion years old (Blakemore et al. 2016). To complement the programs above, natural copper analogs will be assessed, and in some cases tested for corrosion performance. This will provide additional data on the critical container material on a time-scale that is not possible in other experiments, and is orders of magnitude longer than the container is required to last. Where possible, samples encased in their geologically stable material (i.e. clay, or rock) will be taken intact for analysis, and in-situ methods will be used to study them prior to extracting them from these stabilizing materials.

6.7 Research Program Summary

Copper is a very stable metal for DGR purposes; however, the information in this section covers a wide range of possible degradation processes for copper. While many of these processes are very unlikely, copper is such a critical safety barrier for the used fuel container, it is necessary to research these topics to continue to reduce uncertainty in the behaviour of copper.

<u>Site Selection and Characterization Phase</u>

Prior to licensing, it will be necessary to finalize reference processes for the copper fabrication. Degradation testing of the selected coatings will be required, and these tests will have to support the manufacturing specifications for copper purity. In general, the likely contaminants from the manufacturing processes will provide direction for the corrosion programs so that manufacturing can be accomplished using realistic industrial processes. The corrosion allowance for any process causing degradation will be finalized prior to licensing as well.

Methods will also be developed for borehole testing at the site, and accelerated testing will initiate at analog repository locations such as at depth in the ocean.

Site Preparation and Construction Phase

As noted above, research will continue on possible corrosion processes affecting copper within a DGR. As site-specific information becomes available from the characterization efforts during construction, the corrosion allowance will be updated to reflect the site as accurately as possible. Long-term exposures will be initiated in additional boreholes to ensure that the assessment is suitable for the entire repository site, and some samples will be assessed that are initiated in the site-selection phase.

Operations, Monitoring and Closure Phase

As noted above, the broad research program will continue, to further the understanding of the degradation of the container components. UDF experiments will be developed to provide additional in-situ information to reduce the uncertainty of the corrosion predictions.

Major Facilities

No new specific major facilities are required prior to construction. Many of the programs listed above will occur in University and National Laboratory environments, throughout all project phases. The primary facility required during construction is the UDF.

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7 PLACEMENT ROOM SEAL

7.1 Sealing System Requirements

The placement room sealing system mechanically supports the containers and provides a stable, low-permeability, self-sealing transport barrier around them. In the event of container failure, it further provides a chemically sorbing environment to cations, delaying release of contaminants into the geosphere. In the NWMO concept, this sealing system component is referred to as the “buffer” since it stabilizes the environment around the container, and delays or controls interaction with the geosphere and the container. Other seal applications are described in the next section.

The reference placement room sealing system is illustrated in Figure 7-1, which shows the bentonite buffer boxes, gap fill and spacer blocks; the figure inset shows small, all of which comprise the “buffer” in the NWMO Mark II concept. The figure inset shows small blocks of bentonite material illustrating their texture and ability to be shaped to the dimensions required for use in the placement room. Research and development for this sealing system are described in the remainder of this section. Engineering tests on fabrication and placement are addressed in the engineering proof testing program.

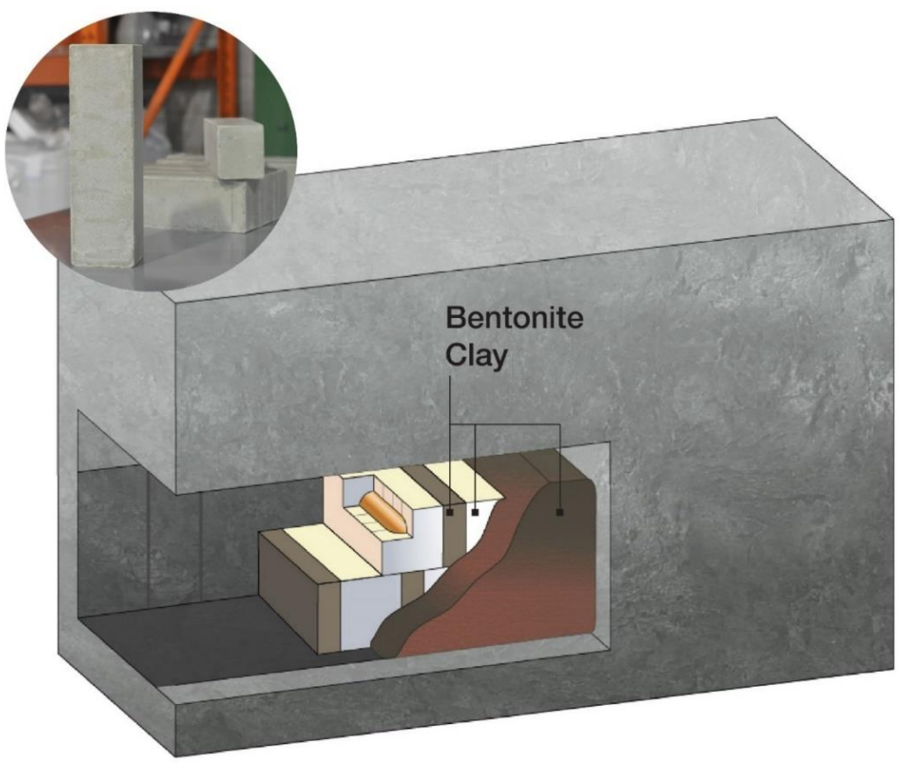

Figure 7-1: Illustration of Placement Room Sealing System

7.2 Room Sealing Requirements

The basic requirements for the room sealing materials are:

- To limit water movement and mass transport of contaminants within the placement room to diffusion. This requires filling the excavated volume of the placement room, the ability of the fill material to swell to fill any installation voids, and exhibit a bulk hydraulic conductivity of $<10^{-10}$ m/s to ensure that diffusion is the primary transport mechanism.
- To mechanically support the UFCs to ensure that they remain in their as-placed locations within the placement room. This will require that the sealing materials located below and around the UFCs exhibit adequate strength and stiffness characteristics.
- To mechanically support the rock around the placement room (preventing growth of damaged rock zone). A minimum swelling pressure of 100 kPa in the placement room is required in order to achieve this.
- To resist relocation or dissolution of sealing materials by contacting groundwater.
- To conduct heat away from the UFC, such that the temperature at the surface of any UFC is 100°C or less.
- To resist physical and chemical and deterioration by the local environment. These include:
    - Chemical interactions between sealing materials and other installed materials (concrete floor, UFC);
    - Chemical interactions caused by radiolysis (from radiation leaving the UFC);
    - Biological processes that could affect contaminant migration or biochemical degradation of the minerals (or the UFC).

7.3 Bentonite Clay Reference Material

Clay-based seals for repositories have been studied in Canada and internationally since the 1980's (Sellin and Leupin 2013). Swelling clay minerals (smectites), such as Montmorillonite have been extensively studied because they expand or swell when wet. These materials are naturally occurring clays that have demonstrated durability on timescales of millions of years.

The reference material for the NWMO repository in-room seal is 100% bentonite. Bentonite is the general product name used for commercially available montmorillonite-rich clays. Moreover, a specific brand of bentonite (MX-80), supplied by American Colloid, has been chosen as the reference bentonite by NWMO due to its large resource base and proven consistency in supplied materials. MX-80 has the advantage of having been used extensively as a reference material in repository programs in Europe and elsewhere, providing an extensive complimentary set of materials behavior information. All bentonite material used in a production setting would need to meet specific procurement specifications.

Key environmental considerations associated with the behaviour of bentonite are the groundwater chemistry, hydraulic conditions, temperature, and geology. For example, groundwaters at repository depths can contain significant quantities of dissolved salts, and salinity is known to decrease the swelling potential and increase the hydraulic conductivity of montmorillonite (Dixon 2000). Temperatures will be limited by design to a maximum of 100ºC for emplacement room seals.

Over the next several years, the NWMO will procure a significant quantity of bentonite, as process manufacturing and serial production are optimized. During the course of this program, a large quantity of data will be generated from the characterization of incoming and manufactured materials. This information will be accumulated into a database, and the data will be regularly reviewed to ensure that the basic requirements can be met by the incoming and manufactured materials on an ongoing basis.

In general, it is expected that the bentonite property database will be updated periodically during the various program phases (i.e. site selection/characterization, construction and operations/decommissioning). It is anticipated that this effort can be achieved through a combination of international collaboration, review of literature, and a continuation of academic funding on the topics of bentonite and clay sciences.

Additional research and demonstration activities relating to bentonite performance around a UFC is described within Section 5.6 and in Section 6.3. In general, they include bentonite as well as copper or other container materials, to identify synergistic effects of the combination of these materials and environmental conditions (i.e. microbiological, high pressure, etc.).

7.4 Fabrication and Inspection

7.4.1 Fabrication of HCB Blocks

The NWMO uses cold isostatic pressing to form Highly Compacted Bentonite (HCB) blocks. Essentially this uses a tank with an internal rubber liner that can be externally pressurized with wate;, the isostatic press ensures uniform force is applied to the bentonite during its compaction. As a result, uniform densities of the HCB blocks are expected.

The blocks resulting from isostatic pressing will need final machining using standard equipment. To demonstrate this ability, NWMO has built a shaping cell. The shaping cell is an enclosed room where temperature and humidity control maintains the integrity of the compacted bentonite block. To date, several full-scale HCB blocks have been fabricated. Up to 40 will be fabricated as part of the planned serial production trials in the proof test program; this will provide considerable information regarding material consistency, stability and handling.

7.4.2 Fabrication of Gap Fill Material

Granular bentonite, referred to as Gap Fill Material (GFM), is manufactured from the same MX80 bentonite used to produce highly compacted bentonite blocks. However, the main difference is that instead of adding water to increase the moisture content, the MX80 needs to be dried to a moisture content between 2-3%. This is required to increase the dry density of the GFM. The MX80 bentonite is flash dried to ensure the material dries quickly without drastically heating the material. The dried material is agglomerated in a dry roll compaction process, where bentonite is fed into counter-rotating wheels that force the granulated bentonite into briquettes. The briquettes are then crushed and sieved into the required particle size distribution to facilitate efficient compaction of the as-placed material.

To date, this process has been applied on an approximately 100-kg small batch scale (Mielcarek and Birch 2016), and will be extended to 1-tonne scale in the near-term to support the proof testing program.

7.4.3 Inspection of Bentonite

Incoming bentonite materials will be inspected. In addition, manufactured materials (i.e. HCB blocks, GFM) will be evaluated, post-processing. At a minimum, these will include a series of tests, mostly derived from ASTM, and specified in Table 7-1.

Table 7-1: Tests for Incoming Bentonite

Title	Purpose	ASTM
As-delivered composition	Test of procured materials to determine mineralogical and chemical composition for consistency	N/A
As-delivered moisture content	Confirm as-delivered moisture content. Important to know how much water needs to be added to or removed from material in order to meet design specifications.	D2216
Grain Size Analysis of MX-80 or GFM	Confirm particle size distribution in accordance with supplier specifications. Need to demonstrate consistency since particle size will impact final density of HCB and GFM.	C136
Specific Gravity of grains and chips or chip fragments	Confirm specific gravity in accordance with supplier specifications. Need to demonstrate consistency since specific gravity will impact bentonite properties.	D1188
Compaction Properties (Standard and Modified Proctor)	Standard and Modified Proctor are common geotechnical tests for determining an optimal moisture content given a standardized compaction effort.	D698 and D1557
Consistency Limits (Atterberg Limits)	Measures the water content at which soil deformation is defined by plastic and liquid behaviour. They provide a simple test of the mineralogical composition (a high liquid limit is usually a sign of high swelling clay content).	D4318
Methylene Blue	Methylene blue index is linearly correlated with cation exchange capacity, which is also related to the montmorillonite content.	C837
Free Swell / Swell Index of Clay Mineral Component	Free swell provides a reflection of montmorillonite content in bentonite, and in turn, of the swelling pressure and hydraulic conductivity of the bentonite upon saturation.	D5890-11
Unconfined Compressive Strength	Strength determination of HCB blocks.	D7012
Thermal Conductivity by Thermal Needle Probe	Measurement of thermal conductivity of HCB block using a transient heat method.	D5334-14:
Saturated Swelling Pressure and Hydraulic Conductivity	Measurement of maximum swelling pressure and hydraulic conductivity of HCB block after saturation.	N/A

As part of the engineering proof testing, a program is being developed to conduct this testing and identify test quantities required for production scale. One guiding document is the ASTM Standard ASTM D3740-12a, “The Standard Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction”. The program will identify tests that must be completed:

- On all products;
- On all lots from which products are derived;
- On occasional destructive samples;
- During upsets in manufacturing; and
- To become a preferred supplier.

7.4.4 In-room Inspection of Gap Fill

During the emplacement activities, gap fill material (GFM) is placed in a narrow region between the buffer boxes and the repository walls. The volume of this dimension and the mass of GFM will be known; thus, an average density of gap fill will be determined, for comparison with the design specification.

However, due to the confined geometry and the gamma radiation from the used fuel containers, it will not be possible to utilize conventional tools to validate the homogeneity of this gap fill density in actual emplacement rooms. Accordingly, research is planned to develop new methods to measure the as-placed density of this volume. Several options are being considered, including the use of modified di-electric and Cone Penetration Test methods, as well as geophysical and standard soil sampling techniques.

The NWMO will be developing methods to determine the range of localized GFM densities within the emplacement room, by;

- Conducting a review of possible methods for determining dry density in field investigations; and recommending which can be scalable to the range required for the as-placed GFM;

- Conducting a series of small scale trials to demonstrate the suitability of the method for narrow gaps, as well as the reliability of methods; and

- Participating in a full scale above ground (non-nuclear) placement trial to demonstrate the selected techniques.

Activities in this area will continue throughout the program (i.e. site selection/characterization, construction and operation), until the NWMO is satisfied with the resolution of density assessments of emplaced GFM.

7.5 Thermal-Hydraulic-Mechanical (THM) Effects

During its service life, the bentonite will experience a range of thermal, hydraulic and mechanical conditions. Most prominently, radioactive decay of the spent fuel will generate heat that is conducted away from the container, while water from the geosphere will move inward toward the container. Both of these processes in turn affect related bentonite properties, including thermal and hydraulic conductivities and swelling, making this a coupled-process. These effects are coupled and therefore discussed collectively below.

7.5.1 THM Properties

The base thermal, hydraulic and mechanical properties of bentonite have been studied for many years. Recent NWMO work has focused on improving the database in support of developing a qualified database for use in preliminary design and licensing, based on reference materials under repository-specific conditions (e.g. Dixon et al. 2018). Summary properties of bentonite-containing clays, but particularly Wyoming bentonite have been documented in various reports, most recently Dixon (2019). This material qualification work will continue in the near term. Additional work would be required if alternative reference buffer materials are proposed.

A particular topic is the potential for change in bentonite properties if it is at high temperatures for an extended period. In the reference NWMO design, the bentonite buffer would be below 100°C at all times, and in practice only small regions of buffer would approach this temperature and for periods of a few hundred years or less. Under these conditions, no significant changes are expected (Wersin et al. 2007). The effect of extended exposure to temperatures of around 100°C continues to be explored in full-scale experiments (see below). The effects of exposure to higher temperatures (above 150°C) is also being explored in projects such as the Nagra-led HotBENT test.

7.5.2 THM Experiments

Testing of buffer performance has been supported by a variety of large-scale experiments. Projects have included international efforts such as Canister Retrieval Test, LASGIT and Prototype Repository at Aspo; FEBEX at Grimsel; HE and FE at Mont Terri; SEALEX at Tournemire; TED at Meuse/Haute-Marne; and EBS at Horonobe. Past work in Canada by AECL includes the Buffer-Container Experiment, the Isothermal Test and the Tunnel Seal Experiment (see Table 2-3).

To complement this extensive effort, and to provide experimental data specific to the reference Canadian design, the NWMO has commissioned a scoping study to obtain concepts for the experimental work from the National Research Council (NRC). The scoping study included an overview of: (i) requirements of material property characterization; (ii) numerical simulation modelling; (iii) experimental validation of thermal response; and (iv) experimental design of coupled heat and moisture laboratory experiments. In addition, there has been some effort put forward to determine suitable scaling of the simulation model, based on dimensionless equations governing the heat transfer process, and links the geometry scaling to time scaling. In short, a series of experiments conducted at a range of reduced sizes, from $1/10^{th}$ to $1/2^{nd}$ scale were determined to be suitable dimensions. Work has been initiated on the first stage of simple geometry and single effect tests.

In the longer term, and once space is available within the UDF at the repository site, companion experiments will be initiated to validate THM predictions. These experiments are expected to be very long term, in some cases, projecting well into DGR operations, to validate both short term effects (i.e. heating and cracking from hot containers) to longer term effects (ingress of site-specific water chemistry and sealing). The details of these tests have not been determined, but may involve both measurements on heated non-nuclear containers as well as instrumentation on a special pilot-facility with UFCs containing used fuel.

7.5.3 THM Modelling

For preliminary design purposes, simple calculations can be used to develop repository concepts. For example, using conservative assumptions with respect to thermal conductivity, it can be shown that an upper container temperature limit of 100°C is achievable provided sufficient spacing exists between adjacent containers (Guo 2018).

However, for optimized design and predicting performance over the extended period, more complex modelling that includes coupled thermal-hydraulic-mechanical (THM) processes is required. Coupled-process modelling of bentonite-based seals has been under development for many years in Canada and internationally, in part reflecting the advances in computational methods. Examples of THM-coupled modelling of full-scale experiments include Guo (2009; 2011), Guo et al. (2010).

Presently NWMO is involved with several international projects relevant to THM modelling, including the Mont Terri FE experiment and the DECOVALEX project. The latter project in particular has supported 25-years of modelling and improved understanding of coupled processes (Birkholzer et al. 2019). These projects are being used to refine and improve our understanding of THM processes important to near-field repository conditions. Our primary code for this near-field modelling is COMSOL, supported by work with CODE-BRIGHT.

In the near-term, NWMO will continue to improve and test its reference THM model through participation in international projects such as DECOVALEX.

The NWMO is also undertaking work to develop and test our understanding of the behavior of our specific near-field emplacement room design. This work, which will be coupled with scale experiments, will consider a range of simple geometries extending to models of the reference container emplacement concept. Specific topics of interest include the potential for buffer block cracking due to temperature-driven moisture re-distribution, and analysis of the buffer homogenization process on timescales relevant to safety assessment (e.g. Malmberg and Birch 2019).

7.6 Chemical Effects

Bentonite clay is a durable material. The reference MX80 bentonite is from thick deposits that formed about 100 million years ago in present-day Wyoming. Within the repository, it is expected to be placed with manufacturing moisture contents of around 20% and 3% for HCB block and gap fill materials, respectively. Gaps and pores within the bentonite that are not filled with water are expected to contain air from manufacturing, meaning some oxygen will be deposited into the repository within the clay. As noted in Section 7.5, the early elevation in temperature from the radioactive decay is likely to dry the bentonite somewhat, near the container, an effect that is resisted by water from the host rock seeping inward. During this period, it is expected that the oxygen will freely travel through the unsaturated bentonite, and eventually be consumed by corrosion, microbial and adsorption processes within the DGR. When the heat decays and water wets the bentonite, a range of chemical species may begin to travel inward toward the container, depending on the site and bentonite characteristics (King et al. 2017). Accordingly, the NWMO will investigate to identify the water chemistry that will occur for the site selected for the DGR. This research will also aim to identify pH, Eh and other important parameters that will define the initial solution that contacts the container.

Further complicating this scenario is the period prior to complete buffer wetting, during which water vapour may be present in the environment. The presence of salt crystals on the surface of the bentonite blocks or the container may induce short-lived localized wetting conditions. While a small amount of bentonite may be altered by elevated hydroxide or potassium levels as described below, localized corrosion may be initiated at such a site. This process is being investigated in ongoing work, which is conducted near the condensation temperature of the bentonite-copper-water system.

For bentonite itself, there are two primary chemical effects of relevance to its long-term performance in a repository: the effect of salinity on swelling, and the effect of certain chemicals that can cause it to change into a non-swelling mineral.

The effect of salinity on bentonite is to reduce its ability to swell, thereby reducing the resultant swelling pressure it applies to adjacent materials in the DGR and to increase the hydraulic conductivity. These effects have been measured for a range of clay materials with varying amounts of montmorillonite (the swelling mineral in bentonite) and water chemistries. The results indicate that under saline conditions likely in a repository in the Canadian Shield, salinity effects will be modest. Under the brine conditions likely in a repository in Southern Ontario sedimentary rock, the effect of salinity will be large, but a high density bentonite would still have sufficient swelling capacity to meet the required pressure and hydraulic conductivity requirements (Priyanto et al. 2013, Barone et al. 2014; Dixon et al. 2019). These conclusions will continue to be confirmed with further tests, including considering the effects of temperature, using reference bentonite products and site-specific groundwater conditions as they develop from the siting program.

Relevant chemical conditions that are known to affect the mineralogy of bentonite include potassium ions in the groundwater, high pH associated with leachate from nearby concrete structures, and potentially high concentrations of iron in groundwater (Dixon 2019). All of these promote the transformation of montmorillonite into illite or other non-swelling minerals, with the rate generally dependent on concentration and temperature.

In general, both repository siting and the research program will consider the potential effect of site-specific groundwater chemistry on the stability of bentonite. The general design basis minimizes the amount of steel and cement in the vicinity of high-performance bentonite as well as the temperature of the bentonite.

7.7 Radiation Effects

In general, the influence of radiation on the structure, mineralogy, and behaviour of bentonite under conditions relevant to the NWMO placement room is insignificant, as extensively documented by Dixon (2019). The NWMO UFC, similar to most containers proposed for use in deep geological disposal provides substantial self-shielding. However, much of the literature on this subject involves tests undertaken under radiological conditions orders of magnitude more severe than will occur – i.e., exposures that do not simulate field conditions (Dixon 2019). To summarize the relevant information, radiation effects will be associated with two very different conditions:

- The first stage in radiation interaction between the used fuel in the UFC and the surrounding bentonite occurs while the UFC is intact and radiation emitting from its surface is limited to gamma rays. Gamma radiation has been concluded to have very limited effects on the structure or behaviour of the bentonite, even under conditions much more severe than will occur in the DGR (Pusch et al. 1992, Jonsson 2012). The bentonite immediately adjacent to the UFC will therefore have undergone little or no radiologically-induced degradation before the UFC is breached.

- The second stage of radiological damage to the HCB will be associated with alpha radiation. This will not begin until the UFC is breached, and alpha-emitting radionuclides escape to allow for short-range interaction with the clay. Alpha radiation has the potential to induce greater mineralogical damage to the bentonite, but the zone affected by this process is generally concluded to be limited due to the poor penetrating ability of this radiation and the ability of the bentonite to retard movement of ions through it. The literature is not consistent with respect to either the degree to which radiolysis will influence bentonite (Safi 2017) or if it will at all (Bradbury et al. 2012). Much will depend on minor elements (e.g. iron) in the bentonite since these have a controlling effect on the chemical processes arising from radiolysis. Additionally, it is recognized that gas generation as the result of radiolytic processes will be very small relative to that associated with the corrosion of the steel insert components once water enters the UFC.

To evaluate what is likely to occur in the case of NWMO's UFC, the first consideration is the actual radiation field that will be experienced by the bentonite. Actual radiation contacting the bentonite will depend on factors such as the age of the fuel, the localized shielding effect of the UFC, which has different thicknesses for head and body and the hydration state of the bentonite. The radiation field as a function of time around a fuel container is illustrated in Section 3.6.

The current design basis assumption is that fuel will be stored for 30 years prior to placement in a DGR. Based on Figure 7-2, the gamma radiation dose rate at the surface of an intact UFC is about 9.6 kGy/a for 30 year-old fuel. Based on these same data, after 10^5 years, the cumulative gamma dose at the contact with the surrounding buffer would be on the order of 510 kGy, and by 10^6 years this dose would increase to approximately 1.8 MGy. Gamma irradiation to similar doses has been applied in relevant studies (Plotze et al. 2003, Sorieul et al. 2008, Jonsson 2012), , and the authors concluded to that the radiation will cause little to no substantive damage to the bentonite.

Based on this, it is expected that the Thermal-Hydraulic-Mechanical properties determined for bentonite materials under conditions of no-radiological field are representative of the long-term behaviour of bentonite in the repository.

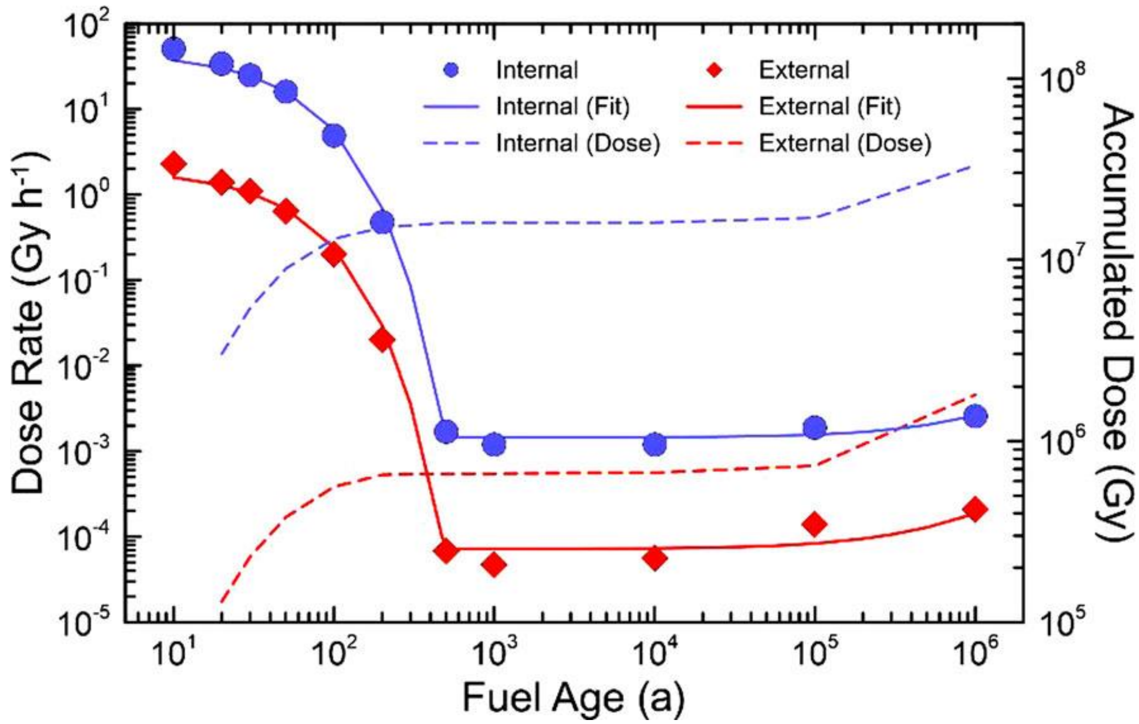

Figure 7-2: Radiation Dose Rate and Accumulated Dose for Outer and Inner Surface of a UFC (Morco et al. 2017)

Despite the extensive evidence that bentonite is not altered by the dose rates of radiation emitted from the UFC, a limited amount of additional information will be sought with respect to irradiation of unsaturated bentonite. The specific investigation considers whether it is possible that the limited amounts of potentially oxidizing species (i.e. hydrogen peroxide, nitric acid, etc.) that have been considered before for saturated conditions may accumulate at a marginally higher rate if they can freely move as gaseous species. Such a process is conceivable for the earliest time period of the repository, where radiation dose is high and water may be limited within the bentonite.

The literature will continue to be monitored going forward on radiation effects. At the repository site, the performance of some emplaced UFCs may be monitored, which would provide further information on this under field conditions.

7.8 Microbial Activity

Once anoxic conditions are established, anaerobic sulphate-reducing bacteria (SRB) could produce sulphides as shown in [8-1] from sulphates naturally present. These could then diffuse through the bentonite and cause microbiologically influenced corrosion of UFCs as per [8-2].

Sulphate reduction $4H_2 + SO_4^{2-} + 2H^+ \rightarrow H_2S + 4H_2O$ [8-1]

Copper corrosion $2Cu + H_2S \rightarrow Cu_2S + H_2$ [8-2]

To prevent the SRB from growing, it is necessary to fabricate bentonite such that sufficiently low water activity can be achieved. High swelling pressures and/or high salinity both achieve this goal as shown in Figure 7-3. To supplement this understanding, recent efforts have included bentonite undergoing changes in humidity (Stone et al. 2016a,b). Results from these studies further demonstrated that microbial metabolism is suppressed at low water activity (Stone et al. 2016b).

The current NWMO bentonite density design specification is an average dry density of 1.6 g/cm^3 for the buffer within the emplacement room. This specification was established based on laboratory pressure cell experiments (40-90 days duration) that demonstrated that growth of bacteria and germination of spores did not occur when bentonite dry densities exceeded 1.6 g/cm^3 (Figure 7-3). A similar limiting dry density was obtained by Motamedi et al. (1996) for some species of SRBs in compacted pure bentonite. Pedersen et al. (2000a, b) also examined the effect of MX-80 bentonite buffer density on various microorganisms, including SRBs, and their ability to produce sulfide over a 28-week incubation period, and determined that the buffer density started to exert an inhibitory effect on sulfide generation at a bulk density of ~1.5 g/cm^3. More recent work by Bengtsson et al. (2015) includes analyses of MX-80 bentonite with “wet densities” of 1.75 to 2.0 g/cm^3, which have an equivalent dry densities of 1.17 – 1.56 g/cm^3. The experiments demonstrated that high density bentonite clay has a considerable ability to suppress sulphate reducing microbial activity vs. the lower density material. This principle has been further demonstrated for Calcigel bentonite (Bengtsson and Pederson 2017).

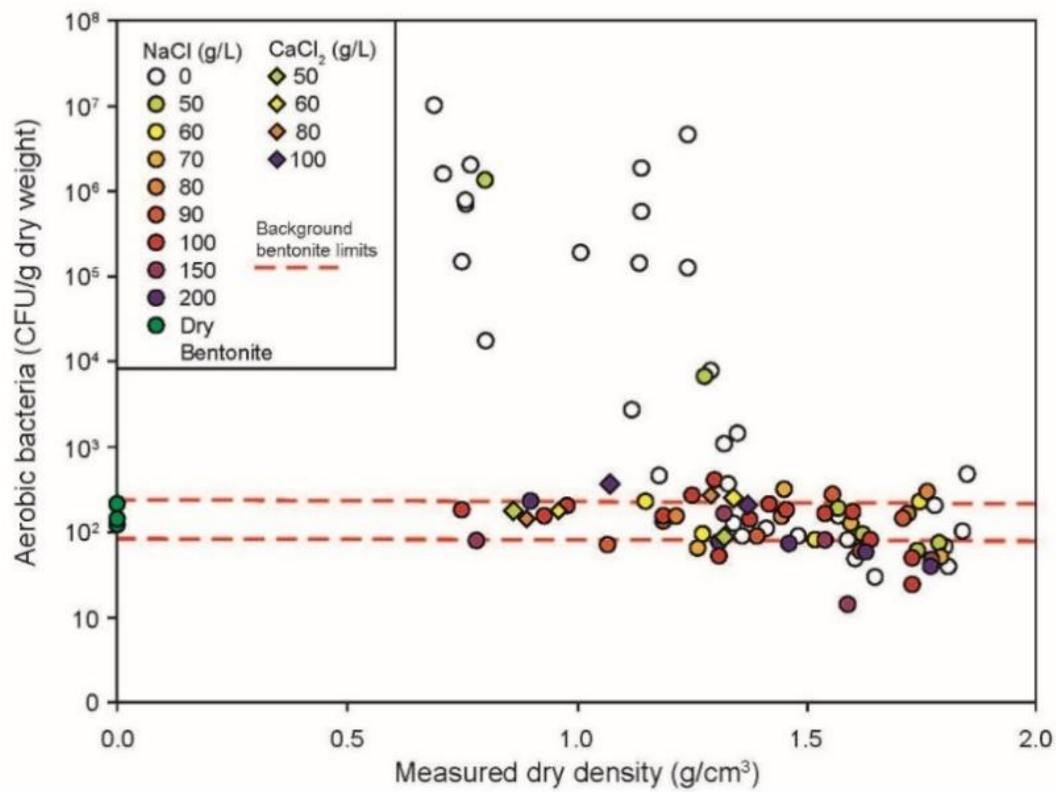

Figure 7-3: The relationship between culturable heterotrophic aerobes versus measured dry density in saturated MX-80 bentonite. The dashed red lines indicate the average number of organisms in dry, powdered MX-80 bentonite, as purchased (modified from Stroes-Gascoyne and Hamon 2008; Stroes-Gascoyne et al. 2010a).

A bentonite dry density of 1.6 g/cm^3 is postulated to limit microbial growth and activity as a result of a combination of the high swelling pressure, small pore space, and low water availability. In addition, because microorganisms require a carbon source, energy source, electron donor, electron acceptor and nutrients to grow and be active, NWMO's R&D program will continue to evaluate carbon and nutrient sources in candidate clay materials. Marshall et al. (2015) has demonstrated how the reference design bentonite (MX-80) and two other commercial bentonites have a low weight percentage of organic carbon. This is not the case in all bentonites as noted in Kiviranta et al. (2016) so care is needed in selection of materials for use as buffer. Through further research, NWMO will further explore the composition of organic carbon in bentonite clay and will develop procedures to minimize the introduction of carbon and nutrients during construction and operations.

Table 7-2: Carbon Content of Bentonite Clay Samples

	MX-80*	CCP*	National*	Wy**	Milos**	Friedland**
Total carbon (%)	0.72	0.47	0.24	0.28 - 0.39	0.75 – 2.07	0.4 - 0.65
Organic carbon (%)	0.11	0.41	0.24	0.15 - 0.6	0.05 - 0.49	0.27 – 0.47
Inorganic carbon (%)	0.61	0.05	< 0.05	<0.19	0.1 – 1.91	0.05 – 0.48

* Marshall et al. (2015); ** Kiviranta et al. (2016)

NWMO bentonite microbial research going forward will generally be focused on pressure cell experiments and borehole module studies, to better incorporate underground conditions; although some lab-only analysis will be used to supplement method development. In addition to classical laboratory tests, NWMO is pursuing options to conduct tests in-situ in various underground laboratories (currently tests at Mont Terri and Grimsel), within boreholes from surface in a relevant Canadian location, and also in ocean test beds which can provide an environment with relevant hydraulic pressures.

7.9 Interaction with Container and Geosphere

The buffer component of the Engineered Barrier System represents the interfaces directly between the used fuel containers and the geosphere. It will conduct heat from the container outwards to the geosphere, and in the case of a failed container will have contaminants passing through. It will also conduct water and dissolved chemicals inwards from the geosphere, and chemical species. These interactions will occur over a large surface area for a very long time.

7.9.1 Sulphide Transport

In addition to the movement of water from the geosphere into the buffer as previously discussed, of particular interest is the possibility of sulphide from the geosphere moving inwards through the buffer and causing corrosion of the container. The NWMO currently carries a Microbial-Induced Corrosion (MIC) allowance of 1 mm of copper corrosion over 1 million years (Kwong 2011; Scully and Edwards 2013). This allowance was calculated assuming 1D transport of a 3 ppm sulphide concentration through bentonite to the container, and uniform simple corrosion (i.e., molar conversion of hydrogen sulphide to copper sulphide). The 3 ppm sulphide bulk concentration for groundwater from the host rock was used as a conservative placeholder until actual sulphide measurements are available.

To refine the MIC corrosion allowance, NWMO has supported the development of a 3D numerical model to evaluate diffusion of sulphide through HCB and evaluate microbiologically influenced corrosion of the used fuel containers (Briggs et al. 2017a,b). The model shows that the highest corrosion rates would occur on the container ends (Figure 7-4).

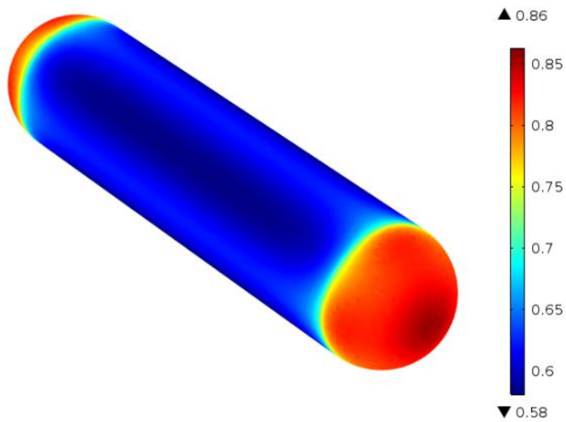

Figure 7-4: Corrosion rate for the case of a single UFC package in nm/year/ppm sulfide. Maximum corrosion occurs at the hemi-spherical end cap.

The NWMO MIC allowance will need to be refined on a site-specific basis. This model will continue to be refined as site- and design-specific information becomes available. It is being expanded to incorporate the following processes:

- Temperature;
- Saturation of the bentonite buffer;
- Mechanistic copper corrosion at the surface; and
- Microbial kinetic reactions, including:
    - Consumption of oxygen and creation of an anoxic environment;
    - Conversion of sulphate to sulphide;
    - Gas production and consumption.

The model will be supported by a variety of experiments, including deep ocean corrosion module tests and sulphide diffusion coefficient measurements in the near-term, and supported by studies in the UDF eventually.

7.9.2 Buffer Erosion

Buffer erosion occurs when water can flow freely within a repository environment. This can be a factor during emplacement where rooms intersect transmissive fractures. In the longer term after emplacement, bentonite buffer in contact with low salinity water in adjacent rock fractures may form colloids that are slowly removed over time, leading to local removal of bentonite. This low salinity water could occur during or as a result of glaciation, even if not currently present at the repository horizon. Studies indicate that erosion is inhibited by small amounts of dissolved salts in the water, and by formation of erosion-resistant deposits (e.g. Vilks and Miller 2010; Neretnieks 2018).

This is an important scenario in some European repository programs, and will need to be assessed at the Canadian site (possibly more likely in a crystalline site, very unlikely in sedimentary site). This is being considered as part of the siting process, and will need to be reviewed as the site characterization program continues (e.g. water salinity at depth, fractures at depth, glacial water penetration to depth).

7.9.3 Gas Transport

Under normal conditions, gas transport in the buffer is assumed to be relatively fast and not important. However in the case of a failed container, it is possible that there will be sufficient production of hydrogen gas from steel corrosion that the ability of this gas to move out from the container through the buffer will be important.

In general, gas transport through unsaturated clays would be relatively fast and straightforward. However if the clay has saturated, as is likely the case if a container has failed (implying water contact with the container), or nearly saturated, then conventional gas transport is inhibited. Classical permeability data can be used to estimate the transport of gas through the clay at low pressures, but at high pressure a different process occurs, often referred to as dilational flow. In this case, the gas is able to dilate the clay and make a passageway that allows for rapid gas movement and pressure equilibration.

NWMO has participated in international gas flow studies, including in particular the SKB LASGIT experiment, the EU FORGE modelling project, the Mont Terri HE-G experiment, and currently the Nagra GAST experiment. Future work will largely involve remaining current with the state of science in this area and participation in international partnerships, which combine underground processes with gaseous transport through various clays. This strategy is particularly viable for this topic as many of the other organizations consider the use of corrodible containers, such as steel (Andra, Nagra, Belgium), where significant gas is expected to be generated.

One ongoing program consolidates work of interest to NWMO, Ondraf-Niras and Nagra on the detection of very small amounts of hydrogen released from copper and steel undergoing extremely slow corrosion. In the latter case, the steel is mounted in concrete or bentonite, and both corrosion rates and gas transport rates are calculated by measuring hydrogen in the headspace. Participation in these programs also allows NWMO early insight into related internal programs conducted by the other international organizations, as these related results are shared.

7.9.4 Radionuclide Transport

In the event of a failed container, water will come into contact with the used fuel, and eventually there is expected to be a pathway by which radionuclides within the fuel could be taken into solution and transported via the groundwater. Ultimately, if this occurred this contamination could move beyond the placement room. Key processes in this scenario are the diffusive transport and sorpive retardation of radionuclides within the buffer material.

As bentonite-based materials are proposed as sealing system components in most repository programs, there is information available on these properties. For example, Ochs and Talerico

(2004) summarizes the effective diffusivities for the SKB engineered clay-based sealing materials; this information was the basis for their SR-Site radionuclide transport assessment (SKB 2010). NWMO has participated in model evaluation of bentonite diffusion experiments using the MIN3P-THCm code, and found good agreement with the benchmark tests (Xie et al. 2014).

Sorption coefficients in bentonite depend in part on the groundwater chemistry. In the Canadian context, this means essentially either a low-salinity crystalline groundwater condition or a saline sedimentary rock. There is a considerable amount of information on sorption on bentonite in low salinity settings, and this international data has been generally used to date, such as Ochs and Talerico (2004). The saline conditions in Southern Ontario are relatively unique, and the NWMO has been supporting a significant effort to develop a sorption database for these conditions. A recent summary of this work is available in Vilks and Yang (2018).

Sorption and related transport studies will continue, and as the Canadian siting program advances, this will be adjusted to reflect the site-specific rock and groundwater chemistsry and redox conditions.

7.10 Natural Analogs

Natural analogs can be useful in providing context or insight into long-term behavior or processes. As they are inherently less well defined than laboratory studies, they may provide more qualitative than quantitative insight.

Natural analogs for bentonite have already indicated that clays associated with uranium ore bodies (notably at Cigar Lake, Cramer 1995) and mudstones with copper, notably at Devon, England (Milodowski et al. 2000) can provide a very long-lived isolating environment for the contained materials.

The NWMO is a member of the international Natural Analogue Working Group, and is currently considering participation in studies of old bentonite deposits in Japan that have been buried under repository relevant conditions for about 10 million years (Ito et al. 2019). Exploratory samples have been obtained and subjected to preliminary review, and further controlled samples are under discussion.

7.11 Research Program Summary

While clay science is a mature field, it is necessary to continue to conduct experiments to improve the understanding of bentonite clay in the repository environment. Topics such as thermal-hydraulic-mechanical (THM) performance of clay, microbiology in clay and clay alteration will be explored continuously, as these are possible upset conditions that affect safety of the repository.

Site Selection and Characterization Phase

The thematic research noted above will continue to ensure that the selected material will perform appropriately in the DGR. In addition, the specific product forms of bentonite will be defined, based on engineering activities, and the degradation processes affecting these components will be verified against generic properties noted. This will be particularly important for the GFM, as it will have a lower density than HCB, and it will be much drier and more prone to change as the water from the host rock begins to saturate it. As a result, experiments and models on the THM of the product forms will be very important to defining the bentonite product specifications.

As noted in previous sections, borehole and ocean modules will contain bentonite, so the performance of the material in the repository analogs will be an important component to the design specification. As it becomes available, site-specific groundwater data will be used in bentonite experiments, to ensure it behaves as predicted.

Site Preparation and Construction Phase

In addition to the broad research program noted above, the continued data generated from the site during preparation and construction will be incorporated into defining the site-specific performance of bentonite. Any material changes in bentonite product form or the room layout will be incorporated into the experimental package, to ensure that the material is suitably emplaced within the repository to provide safety.

Operations, Monitoring and Closure Phase

Work will continue with respect to improving the understanding of bentonite clays in general. As early as possible, bentonite will be placed into the Underground Demonstration Facility to obtain site-specific performance data, in support of the existing data. Heating of bentonite and monitoring its performance during interaction with the host rock will be important with respect to verifying THM behavior and engineered seal performance. Samples will be periodically retrieved / replaced to allow for characterization over the course of operations.

Major Facilities

Selected bentonite fabrication equipment have been commissioned by NWMO; however, no new specific major facilities are required prior to construction for R&D. Many of the programs listed above will occur in University and National Laboratory environments, throughout all project phases. The primary facility required during construction is the UDF.

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8 TUNNEL, SHAFT AND OTHER ENGINEERED SEALS

This section discusses the research needs to support the understanding of engineered seal systems within the repository. For the highly compacted bentonite and gapfill materials that may be utilized for both placement rooms and elsewhere in the repository, research is described in the previous chapter.

Table 8-1 (NWMO 2015) identifies the main sealing system applications, materials and their purpose(s) for NWMO's DGR concept.

Based on extensive work previously conducted in Canada and internationally, several materials have been proposed as potential components of these sealing systems. These materials are described by Baumgartner (2000) and are summrized in Table 8-2. Some additional components have been added since Baumgartner (2000) (e.g. asphalt, clay-sand slurry) and these are also included in Table 8-2. Ultimately the seal designs will be formalized that identifies which of these materials will be used and how, but until then each material is maintained as a potential component of the repository sealing system.

The factors and processes considered here with respect to these engineered seals are discussed in terms of the following topics:

- Seal materials
    - Concrete-based seal materials
    - Asphalt-based seal materials
    - Bentonite/sand seal materials
    - Tunnel backfill
    - Grout
    - Borehole seals
- Durability and compatibility
- Seal performance and demonstration

Table 8-1: Repository Sealing Applications

Application	Candidate Materials[1]	Purpose
Room End Plug	• Highly Compacted Bentonite • Low Alkalinity Concrete • Gapfill	Isolates placement room from tunnels, especially during the operating period when tunnels remain open.
Tunnel Backfill	• Dense Backfill • Light Backfill • Low Alkalinity Concrete • Standard Concrete	Seals tunnels to avoid open passages for movement of water and oxygen after repository closure. Provides mechanical support for tunnel roof and room end plugs.
Shaft Seal	• Highly Compacted Bentonite • Bentonite/Sand Mixture • Low Alkalinity Concrete • Asphalt • Standard Concrete	Provides seal through these openings in the geosphere to prevent rapid groundwater path from repository to surface.
Borehole Seal	• Highly Compacted Bentonite • Bentonite/Sand Mixture • Low Alkalinity Concrete • Asphalt • Standard Concrete	Provides seal through these openings in the geosphere to prevent rapid groundwater path from repository to surface.
Fracture / EDZ Seal	• Grout	Decreases the permeability of fractures and damaged rock that intercepts repository or surrounds excavations.
Room Preparation	• Highly Compacted Bentonite • Light Backfill • Clay Slurry • Low-alkalinity, high performance concrete	Smooths walls, evens floors of room in preparation of emplacement activities

[1] Seals may use combinations or layers of materials.

Table 8-2: Repository Sealing Materials

Material Designation	Nominal Composition	Placement method
Highly Compacted Bentonite (HCB)	100% bentonite clay	Placed as pre-formed blocks or bricks in cut-off seals
Gapfill (GF)	100% bentonite clay in the form of well graded crushed pellets/chips	Placed at low to medium dry density by mechanical methods
Bentonite-Sand Mixture (BSM)	Bentonite clay mixted with silica sand or crushed rock. Nominal 70/30% by weight	Compacted in-situ in thin lifts
Dense Backfill (DBF)	70% crushed rock, 25% lake clay and 5% bentonite by weight	Placed as pre-formed blocks or compacted in-situ
Light Backfill (LBF)	Mixture of bentonite clay and crushed rock in the form of dense pellets (e.g. 50% bentonite and 50% crushed rock)	Placed at low to medium dry density by mechanical methods
Clay Sand Slurry (CSS)	Water slurry of bentonite clay and sand	Sprayed directly on surfaces using gas pressure and a supersonic nozzle
Low-alkalinity, High-Performance Concrete (LHHPC)	Standard sulphate-resistant concrete mix with some cement replaced by silica fume/flour	Poured in place as an structural component of sealing systems or as a working (floor) surface
Conventional structural concrete	Sulphate-resistant Portland cement with aggregate	Poured in place
Grout	Fine cementitious materials	Injected under pressure as a slurry into fractured or porous volume
Asphalt	Mixture of bitumen and sand/crushed rock, possibly small amount of lime	Poured in place (hot)

8.1 Seal Materials

8.1.1 Concrete-Based Seal Materials

Concrete is considered as a sealing system component because it provides good mechanical support, is readily handled, and can fill a variety of shapes. It also has a relatively low hydraulic conductivity, at least initially. Concrete will be used as cap seal for shafts, as tunnel support and/or to provide a floor for access tunnels and placement rooms. Fine-grained cementicous or silica-based grouts may also be used for sealing fractures or high porosity volumes around openings, and to mitigate the effects of the excavation damage zone in the rock. Concrete intended for long-term (postclosure) durability would not contain rebar or metal re-inforcement.

There are two types of issues with concrete: durability of the concrete itself, and its potential chemical effects on neighbouring materials due to its alkalinity.

Martino (2006) assessed the issues affecting the durability of concrete in a deep geological repository. In addition to mechanical cracking, the relevant degradation mechanisms are alkali aggregate reaction, carbonation, chloride attack, sulphate attack, interaction with other repository materials, leaching, abrasion, and for near-surface concrete, freeze thaw cycling. Most of these mechanisms require some groundwater movement into, through or in the volume surrounding the concrete; if this does not occur, many of these mechanisms will only have minor effects. These have been considered in the reference mixture design, and will need to be reviewed for the site-specific groundwater conditions.

The major concern identified with the use of concrete is the cement's alkalinity and its potential for alkaline leachate from concrete reducing the swelling characteristics of bentonite seals within the repository. Consequently a low-alkalinity concrete is proposed for use in much of the repository. AECL originally developed a low-alkalinity concrete by using substitutes for some of the cement used in traditional concrete (Gray and Shenton 1998, NWMO 2015). This new material had a reported pH in the range of 9 to 10 (Dixon et al. 2001), much lower than regular Portland cement with pH ~12. This low-alkalinity mix also had lower heat generation due to the reduced cement content, which in turn minimized cracking during curing, and it had higher strength than conventional concrete. Other national programs have developed similar low-alkalinity mixes (e.g., Vogt et al. 2009, and Holt et al. 2014). Overall, these lower-alkalinity, lower-heat, higher-performance concretes are designated as Low-Heat, High-Perfomance Concrete (LHHPC) and are the preferred cementitious material for use in much of the repository.

In 2014, NWMO completed a series of basic physical and mechanical tests on an LHHPC mixture similar to the AECL formulation, to confirm baseline properties and also to determine the effect of high groundwater salinity on their behaviour. Figure 8-1 shows the concrete specimens for testing. Tests on the LHHPC were carried out using distilled water and water with a salinity of 270 g/L (SR-270). The test results indicate that the LHHPC samples had very low porosity and very low hydraulic conductivity (< 10^{-13} m/s). At 270 days of curing, the unconfined compressive strength of these samples approached 95-100 MPa. These initial tests show that LHHPC can provide a low hydraulic permeability barrier to groundwater movement and good mechanical support to overlying materials.

Figure 8-1: LHHPC Specimens After Curing in SR-270 (left) and Distilled (right) Waters

Work by NWMO on optimization of the LHHPC formulation was carried out from 2015 to 2018. Some concrete ingredients in the original 1990's AECL reference formulation (e.g., super-plasticizer and speciality cement) are not presently commercially available, so alternative formulations were evaluated that use ingredients from local and sustainable sources. An optimized mix has been developed (Aldea et al. 2019). Within material testing data available to date, the performance of the optimized LHHPC design is similar to, or exceeds, the original mix. In particular, the optimized mix achieves as low a pH (9-10) as the originally reported materials. The work to date has therefore identified a reference concrete mix for use as the basis for further studies.

The ongoing and planned technical research program has the following elements:

(1) Work will continue in the near term to characterize the transport properties of the optimized LHHPC mix. These will include measurements of diffusivity, sorption properties, two phase gas/water properties, confirmation of other key properties such as saturated hydraulic conductivity, pH, porosity, maximum temperature rise, and other basic mechanical properties when exposed to waters with varying salinity.

(2) As the siting program develops, tests will also be conducted on site specific materials, including site-relevant groundwater chemistry as well as relevant sand or crushed rock materials obtained locally. The groundwater conditions will reflect those from all layers where concrete may be used, from shallow structures where low salinity is expected to the repository horizon where high salinity conditions are anticipated.

(3) Studies of the resistance to degradation will be carried out in the context of site-specific aggregates and groundwater composition. These will initially be based on expert review and modelling, and then extended to short and long duration tests.

The objective of this program is to identify and qualify a reference LHHPC with a good database of material properties. Longer duration and performance-related testing is described later in this report. No specific research is presently planned on standard concrete materials for use in the repository; this material might be used in locations remote from bentonite seals such as near-surface structures.

8.1.2 Asphalt-Based Seals

Asphalt-based materials are being studied as an alternative shaft seal material that can provide short-term sealing, and redundancy in long-term seal performance due to their different chemical nature from clay and concrete-based seals. Asphalt is a mixture of bitumen with sand or gravel, commonly used for surfacing roads and for roofing. These organic based, natural deposits range in age from thousands to millions of years old under geological conditions. It is highly resistant to most acids, salts, and alkalis (WIPP 2009). Bitumen is widely used as a water seal material in concrete structures. Bitumen has also been used as a sealing material in the design of various low and intermediate level wastes.

Asphalt or bitumen-based materials have been proposed for use in shaft sealing at the US Hanford site (Freeman and Romine 1994), the U.S. Waste Isolation Pilot Plant (WIPP 2009), the OPG L&ILW DGR (Quintessa and Geofirma 2011, Section 4.4.3), and at Morsleben (Stielow et al. 2016).

The NWMO reference asphalt seal mixture is based on the composition proposed for the shaft seal at WIPP (WIPP 2009). This composition contains 70% silica sand, 20% asphalt (AR-4000), and 10% hydrated lime. The sand increases the rigidity and strength of the material and reduces shrinkage. The lime increases the stability of the material, decreases moisture susceptibility and acts as an anti-microbial agent.

In 2014, NWMO completed an initial series of physical and mechanical tests on a reference asphalt seal material. Performance graded asphalt cement 64-22 (PGAC 64-22), a commercially available alternative to AR-4000, was used. Figure 8-2 shows the specimens subsequently tested. Permeability tests on the asphalt were carried out using distilled water and water with a salinity of 270 g/L. The test results indicate that the asphalt samples had very low porosity and very low saturated hydraulic conductivity (< 10^{-13} m/s). These initial tests confirm that the asphalt mix can provide a barrier to groundwater movement.

Studies of asphalt aging in the pavement industry have indicated that the main factors relevant to aging are temperature, ultraviolet exposure, rainfall and exposure time (to oxidation by air, mechanical wear) (Sirin et al. 2018). However, most of these factors are not relevant to repository seal application, as the materials will be used deep underground and in the longer term are under anaerobic condition.

WIPP (2009) indicates that sufficient information is available to ensure performance of the asphalt component for its relatively short-term requirements, but verification tests would be useful to optimize the mixture, refine the viscoelastic properties at repository temperatures, conduct accelerated aging tests, and to demonstrate durability in brine.

NWMO work plans to continue to review the reference asphalt-based mixture and optimize the mixture based on aggregate from site-specific sources and groundwater chemistry. Further, the transport properties of the asphalt seal mixture need to be measured in order to assess system performance. These tests include porosity, diffusivity, hydraulic permeability and gas permeability.

Longer term durability and performance testing is described in Section 8.2.

Figure 8-2: NWMO Asphalt-Based Materials Specimens for Testing

8.1.3 Bentonite/Sand Based Seals

The primary component of many of the engineered seals is bentonite clay, with the particular composition somewhat dependent on the specific application. Bentonite clay-based seals for repositories have been studied in Canada and internationally since the 1980’s (Sellin and Leupin 2014). As noted in the previous chapter, highly compacted bentonite and gapfill will be in the emplacement room, immediately adjacent to the container. However, these products may also be used in more remote regions of the repository, as per Table 8-1.

The reference NWMO bentonite for research and development is repository-grade MX-80. This product possesses a high montmorillonite content and is capable of high sealing performance applications notably around the used fuel containers. For locations where low porosity and mechanical support are the main purposes, such as in bulk tunnel seals, possible materials are MX-80 bentonite blended with sand (Bentonite Sand Material), or non-swelling clays and crushed aggregate (Dense Backfill) (Noronha 2016).

The primary shaft seal material is a bentonite-based material, because it swells when saturated with water and provides a high quality seal. However for the shaft seal, 100% bentonite is not required, as there is no microbiological requirement for this region of the repository. The addition of a sand or finely crushed rock or finely crushed rock component produces a mixture that is easier to handle, including in a wet environment. It also uses more local material and less bentonite, so it may be a more sustainable choice.

For the NWMO shaft seal, a reference bentonite-based material that is 70% bentonite and 30% silica sand by dry mass, was identified for further study. This material has been selected for the OPG L&ILW DGR, based in part on its expected ability to provide sufficient sealing even under saline conditions expected in sedimentary rock settings. This expectation was based on the observed scaling of key properties of mixtures of clays, notably hydraulic conductivity and swelling pressure, with the montmorillonite content of the material.

This 70/30 bentonite/sand mixture (BSM) has been studied under saline and freshwater conditions (Priyanto et al. 2013; Barone et al. 2014; Dixon 2019), and more work is underway. The testing program involves basic physical, chemical and mineralogical characterization tests of the bentonite and sand. The geotechnical characterization includes: free swell tests, consistency (Atterberg) limits tests, modified compaction tests, triaxial and 1D-consolidation tests, swelling pressure, and hydraulic conductivity tests to determine mechanical properties, gas permeability, and determination of soil-water characteristic curve (SWCC). Reference waters, containing approximately 0 (distilled water), 10 (CR-10), 160 (SR-160), and 270 (SR-270) g/L of total dissolved solids, have been used to determine what effects salinity would have on the post-placement behaviour of this seal material.

Initial compaction testing established that a dry density of 1.80 Mg/m^3 was readily achievable using conventional dynamic compaction methodology; therefore, the reference dry density of this seal material is defined as 1.80 Mg/m^3 for the testing program (Priyanto et al. 2013).

The hydro-mechanical testing in Barone et al. (2014) indicates that at the as-placed dry density of 1.80 Mg/m^3, the seal material specimen maintained a saturated hydraulic conductivity of less than 10^{-11} m/s and a swelling pressure in excess of 0.6 MPa when the groundwater salinity is 160-270 g/L. Freshwater or very low total dissolved solid groundwater system exhibits hydraulic conductivity of less than 10^{-12} m/s and a swelling pressure in excess of 3 MPa. The ability of the seal to transmit gas through its pore spaces when the specimen is unsaturated as well as its suction-moisture behaviour has been investigated. The gas conductivity for these materials ranged from 10^{-7} to 10^{-11} m/s depending on porewater composition and degree of saturation, when tested with air as the permeant and compacted to the target dry density. At a degree of saturation of 85%, the gas conductivity was in the range of 5×10^{-10} to 1×10^{-11} m/s. This corresponds to gas permeabilities in the range of 7.5×10^{-15} to 5×10^{-16} m^2.

This indicates that this 70/30 bentonite/sand mixture is a potentially suitable material for use in shaft sealing, as it provides a low hydraulic conductivity and will develop a substantial swelling pressure when saturated with water. However, further work started in 2018 to confirm or identify the optimized mixture by evaluating the seal behavior of bentonite/sand mixtures having composition ratios other than 70/30. In this study, the use of a crushed limestone based sand material is being studied, in addition to granitic sand. Composition ratios of bentonite/sand mixture of 50/50, 60/40, 70/30, 80/20 and 90/10 at ~1.8 Mg/m^3 dry density are being assessed. Different salinity waters are used. Basic physical and geotechnical properties of fabricated materials are being measured.

Once the optimized bentonite seal mixture is determined, work is planned to further characterize the optimized mixture. These will include measurements of diffusivity and sorption properties, and confirmation of other key properties such as swelling pressure, saturated hydraulic conductivity and two-phase gas/water properties.

This work will be ongoing for the near-term, in order to strengthen the database on the reference BSM properties, including providing information on batch-to-batch variability. As the siting program develops, tests will switch to site specific materials, including site groundwater chemistry as well as relevant (i.e. regionally sourced) sand or crushed rock materials.

While not currently an active research topic for the NWMO, the emplacement of bentonite-sand mixtures via the spraying of slurries is an ongoing research subject for other international programs, including Japan (Suzuki 2014). Should this operational method become favourable for tasks such as room preparation, it will be necessary to characterize bentonite-sand mixtures applied by this technique, as noted above (i.e. diffusivity, sorption, etc.)

The result of this program will be a reference shaft seal BSM with a good database of material properties.

8.1.4 Tunnel Backfill

The tunnel backfill is the material used for filling the tunnels on closure of the repository. The basic requirements are that this backfill should maintain a swelling pressure of 100 kPa (to provide support to the surrounding rock), provide a hydraulic barrier to groundwater flow, be largely based on locally sourced materials, and be readily placeable in the underground. This is expected to consist of two components – a dense backfill (DBF) material used to fill the bulk of the space, and a light backfill (LBF) or Gap Fill Material (GFM) used to fill in the remaining space primarily along the roof of the tunnel to ensure no open gaps for direct water flow.

Based on work by AECL (Baumgartner 2000), the main components of the backfill are locally sourced aggregate and a glacial lake clay. Glacial lake clays are more locally available in Canada than bentonite clay, but also contain less (or no) swelling minerals. Consequently, a small percentage of bentonite clay is added to ensure the requirements for swelling and low hydraulic conductivity are met, with a resulting mixture of about 70% crushed rock, 25% lake clay, and 5% bentonite clay (NWMO 2015).

In the Posiva reference closure design, the tunnel backfill is similarly based on a clay-aggregate mix, but with a range of mixes depending on the local importance of local water flow control, and the use of hydraulic (bentonite-based) plugs at strategic locations (Sievanen et al. 2012).

Further development of this material would be conducted in the context of specific site, in order to be based on locally available materials.

8.1.5 Grout

Grouting is a long established method that can limit water flow in fractured rock. The basic requirements for grouts are that they can be injected into narrow spaces, can provide a hydraulic seal, and can withstand hydraulic erosion and desiccation.

Grout will be required for operational water control underground, to reduce the water inflow rate in regions where water-bearing fracture zones intersect the repository and shaft. They may be also be used in areas with high rock damage, to reduce their hydraulic conductivity.

Grouts are often cementitious materials, but since cement may reduce the performance of bentonite seals depending on pH and how much there is, bentonite clay-based and silica-based materials have also been tested for repository applications (NWMO 2015). Examples of field trials include trials in a fracture zone at the AECL Underground Research Laboratory in 1987 and grouting around the TSX concrete bulkhead (NWMO 2015). Internationally, grouting techniques and mixtures for Posiva’s underground facility are described in Posiva (2013).

Owing to the limited use presently expected in the repository, and the absence of a lifetime requirement, no specific development of grout is presently planned by the NWMO. Practical experience in tests and in operation of URLs and mines will be monitored, and used to inform NWMO planning in advance of construction of its repository.

8.2 Durability and Compatibility

There are several factors relevant to demonstrating the longevity of the borehole seal. These include ensuring that there is no significant negative chemical reaction between the seal materials and surrounding materials, including other seal components, the surrounding rock and groundwater. All seals will be exposed to the groundwater chemistry present at the repository site. These seals will also be exposed to temperatures up to around 50°C or so, based on their location relative to the used fuel containers; future THM modeling (Section 7.5.3) will verify the upper temperature limits. The sealing materials should further retain their mechanical integrity and ability to hold up under the weight of the material above them, as well as resist erosion by water particularly in the vicinity of fractures.

The basic evidence supporting the durability of the seal materials proposed for use is their demonstrated natural durability. Bentonite clay and bitumen in particular are naturally occurring, with ages in the millions of years in some deposits. A natural analog of cement provides some information supporting its long-term durability (Wetton et al. 1998), but specific cement mixes similar to the LHHPC were first used by the Romans about 2000 years ago, and provide evidence of durability on that timescale.

This information is supplemented by experience working with these or similar materials in a variety of engineering projects, such as the oil and gas sector, which uses cement to seal abandoned wells (AER 2018).

Information specific to the development repository seals is further based on experiments and modelling. Some major experiments are described in the next section. These tests typically operate for periods of years.

NWMO is presently participating in “lab scale” tests on durability/compatibility of seal materials include MaCoTe and HotBENT in the Grimsel Test Site in Switzerland (HotBent 2019).

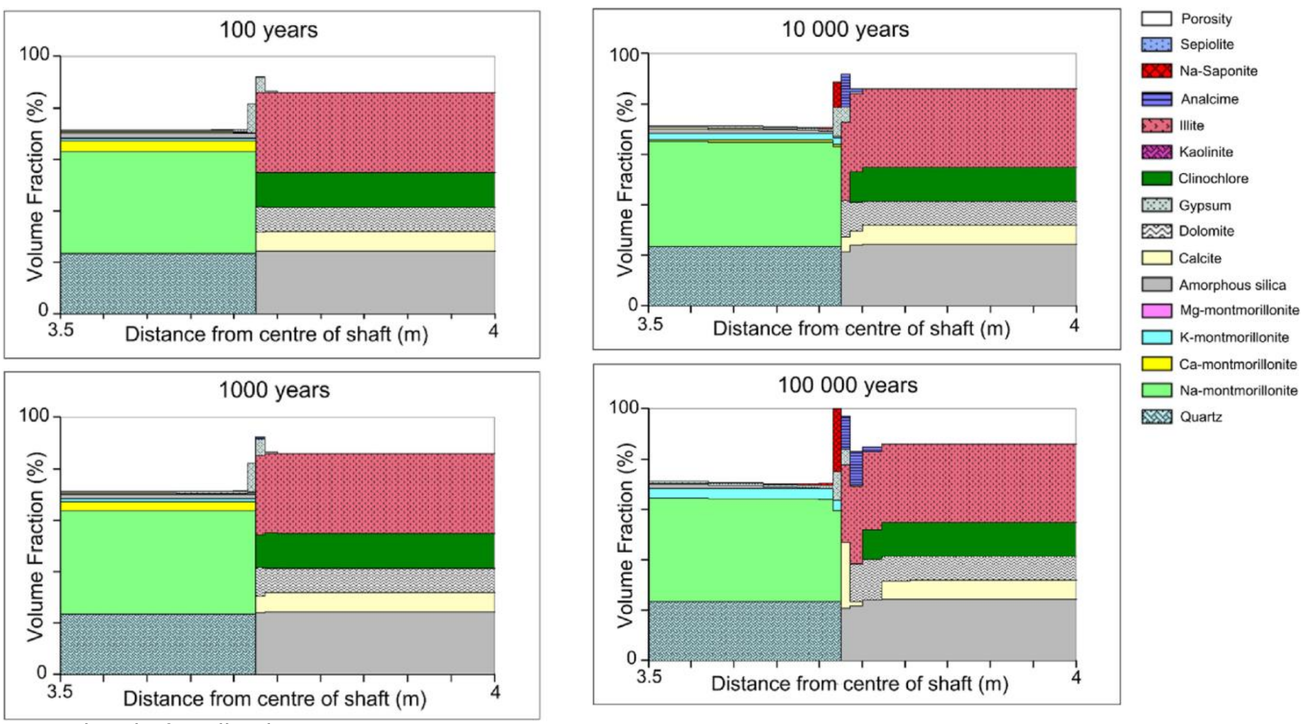
When a site has been selected, some in-situ passive materials compatibility tests will be installed in boreholes from surface, either at the site or in similar rock formations elsewhere (e.g., quarries). As part of the construction for the repository, further in-situ tests will be installed to provide direct long-term information on the behavior of the sealing materials in the actual repository conditions. These could include passive material tests in boreholes installed from the Underground Demonstration Facility (UDF) or in host rock block samples removed during excavation. Some engineering tests will be constructed during the operating period, including test room end plugs as part of the UDF or a pilot emplacement room. The influence of synthetic site-specific pore water on the swelling pressure, hydraulic conductivity and other properties will also be determined in a laboratory testing program.

Long-term durability is also documented further through numerical modelling. Some of this is thermodynamic modelling, done to determine the equilibrium end-state. Current modelling also often includes a transport component, which may be the rate-limiting step in the reactions.

An example of this is geochemical modelling of the shale-bentonite interaction in a hypersaline environment, representative of shaft seals in Southern Ontario sedimentary rock (Wilson et al. 2017). Figure 8-3 shows the base case simulation results. The ‘base case’ simulation suggests that there would be rapid partial replacement of Na- montmorillonite with Ca-montmorillonite in the bentonite/sand, followed with K-montmorillonite then replacing Ca-montmorillonite over longer timescales (tens of thousands of years). Over 100,000 years, minor alteration of the primary minerals at the shaft seal-rock interface occurred in this model, resulting in a reduced porosity alteration zone with a thickness of a few centimetres.

Similarly preliminary geochemical modeling was also carried out to study the LHHPC - Cobourg Limestone interaction in a hypersaline environment. The results showed a zone of alteration of the concrete at the interface with the Cobourg Limestone host rock, occurring over tens of thousands of years, with complete pore occlusion occurring at the interface after ~50,000 years. Overall, the reduction of porosity at the seal-host rock interface suggests that the function of the concrete seal should not be degraded in this case and in fact, could be enhanced due to the clogging of pore volume in the concrete.

The NWMO is presently supporting the development of the reactive transport code MIN3P-THCm to provide further insight. (Xie et al. 2015). Current work includes improving the gridding capabilities, and application to some field studies.



Note: The shaft radius is 3.725 m.

Figure 8-3: Calculated Mineral Volume Fraction Plots for a Bentonite/Sand - Shale Interface at Different Times

8.3 Seal Performance and Demonstration

NWMO presently monitors developments in the long-term performance of seals by participation in international projects. Future work will be done primarily in the context of future collaborative efforts, and site specific studies as part of the site construction and operation phase.

8.3.1 Room End Plugs

The room end plug isolates the filled placement rooms from the access tunnels. The general requirements on the room end plug are given in NWMO (2015). During the initial decades of the operational and extended monitoring phases, the plug keeps the buffer rooms confined mechanically and hydraulically while the access tunnels are open. After repository closure, the access tunnels are backfilled, so each plug is supported on both sides and the hydro-mechanical demands are relaxed. The reference room end plug concept is a composite bentonite and concrete structure, as illustrated in Figure 8-4.

The first test of a simple concrete plug was conducted in the Stripa mine in Sweden in the 1980s, identifying interface seepage as a major concern. Subsequent tests in other projects have achieved acceptable seepage along the plug-rock interface through use of a bulk bentonite seal section in association with concrete to provide mechanical support, or by installation of a layer of bentonite between concrete and rock, or by grouting the rock-concrete interface (Grahm et al. 2015).

Full scale end plug tests have been installed in a several underground tests (see Table 8-3). Experiments and field demonstrations have established that various conceptual designs can be constructed in both lined and unlined tunnel systems. (NWMO's DGR will be located in rock that does not require lining to provide structural support to the openings and so some tests undertaken in sedimentary formations are less directly relevant.) Conceptual designs tested include single-ended plugs as well as dual-ended plugs. Literature reports include development of concrete placement methodologies involving both poured self-compacting concrete and also shotcrete materials that have potential for use in less complex installation.

There are still technical challenges. Included is the nearly universally reported need to be able to grout the concrete-rock interface after the concrete is cured. Curing shrinkage of the concrete is generally sufficient to induce some degree of interface disruption that subsequently needs to be remediated (usually by contact grouting). Achieving adequate gap fill-type densification in systems where augering is used is also an issue that requires consideration when developing placement room sealing system design options.

The NWMO is continuing to monitor the results of these tests, and actively supporting some. End plug tests specific to the APM repository would be constructed as part of the underground testing at the actual site.

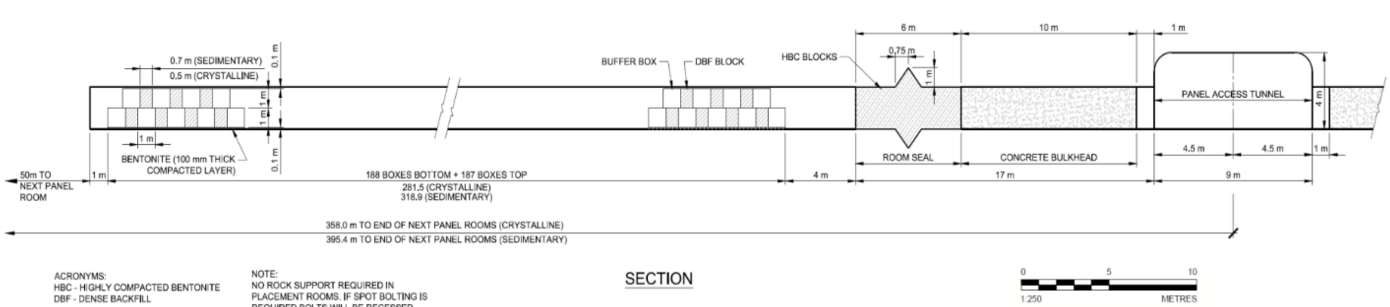


Figure 8-4: Placement Room Concept Showing Room End Plug (Noronha 2016)

Table 8-3: Room Eng Plug Tests

Test / Facility	Components	Physical Scale	Time Frame	Reference
FISST (Finland)	Unreinforced low-pH concrete plug, in granite Heated containers.	~3.5 m x 4.4 m oval tunnel, to be pressurized to 4.5 MPa	Install 2016-2018 Start 2019	Holt and Koho 2016
FE (Switzerland)	Concrete plug in sedimentary rock	~3 m dia. x 5 m long	2015-ongoing	Muller et al. 2017
GAST (Switzerland)	Concrete plug in granite Gas permeable seal	3.5 m dia. x 14 m	2015-ongoing	Nagra 2019
Prototype Repository (Sweden)	Two plugs, reinforced concrete dome-plug, in granite. Heated containers	2.5 m dia. x ~1 m long. Operated with ~1.6 MPa, ~20ºC at plug	2001-ongoing	Svemar et al. 2013 Goudarzi 2019
EPSP (Czech Republic)	Bentonte seal between fibre-shotcrete supports, in granite	~ 3.6 m dia. x 6 m long. Pressurized to 1.2 MPa	Built 2012-2015 Operated 2015-2016	Svoboda et al. 2016
FSS (France)	Bentonite seal between concrete supports, at surface	~7.6 m dia. x 36 m long	Design 2012-2014 Install 2013-2014 Operated 2015	Foin & Bosgiraud 2016 Noriet et al. 2016
DOMPLU (Sweden)	Bentonite seal with unreinforced low-pH concrete, in granite	~4 m dia. x 6 m. Pressurized to 4 MPa.	Install 2013 Operated 2013-2017	Åkesson 2017 Enzell and Malm 2018
POPLU (Finland)	Reinforced low-pH concrete, in granite	~4 m dia. x 6 m. Pressurized to 4.3 MPa	Operated 2014-2016	Korkeakoski et al. 2016
TSX (Canada)	Two plugs, one low-pH concrete plug and one bentonite clay, in granite	3.5 m x 4.4 m oval tunnel x 2.7 m long. Pressurized to 4.2 MPa, heated to 65ºC.	Operated 1995-2004	Dixon et al. 2016 Martino et al. 2006
FEBEX (Switzerland)	Concrete plug, in granite. Heated container.	2.7 m x 2.3 m oval tunnel. Operated with ~0.5 MPa, ~20ºC at plug	Operated 1994-2015	Villar 2006 2017 Lanyon et al. 2013

8.3.2 Shaft Seals

The Shaft Sealing System is a low-permeability structure installed to fill and seal the shafts. Shaft seals are not close to the placement rooms, so they will experience lower temperatures than placement room seals. However, the shaft sealing system may pass through different rock layers with appreciably different properties in terms of hydraulic characteristics, groundwater salinity and redox conditions, and physical strength.

NWMO has a reference shaft seal design concept; however the final design will depend on the site geology. The shaft seal concept includes use of clay, cement and asphalt-based materials in layers. These layers will have different, but complimentary functions, including:

- LHHPC concrete cap at surface,
- 70/30 bentonite/sand compacted in-situ for bulk rock zones,
- LHHPC concrete bulkheads keyed into rock or overburden in strategic locations, notably around permeable zones,
- Asphalt layer in a bulk rock zone as an independent low-permeability material, and
- A LHHPC concrete monolith at the repository horizon to provide mechanical support to the shaft seal.

The concept is based on the following considerations:

- Planned shaft seals in other repositories, in particular, the U.S. Waste Isolation Pilot Plant (WIPP), and the proposed Ontario Power Generation's DGR for Low and Intermediate Level Radioactive Waste (L&ILW) at the Bruce nuclear site.
- Use of different materials for redundancy and for optimizing system performance under the variable conditions occurring along the shaft.
- Use of durable materials that can be placed in bulk form.

The main areas of technical research related to shaft seals are the following:

- Optimization of shaft seal materials for site-specific conditions;
- Characterization of shaft seal materials; and
- Demonstration of long-term durability.

From an engineering perspective, other factors to consider are:

- Developing shaft seal material specifications and acceptance tests; and
- Demonstration of shaft seal system placement and performance.

Presently there have been few large-scale repository shaft seal tests, see Table 8-4. However, the design can be informed to some extent by conventional mine shaft seals (especially concrete seals), and by other large-scale repository sealing tests as described in other sections of this report.

Table 8-4: Shaft Seal Tests

Test / Facility	Components	Physical Scale	Time Frame	References
ESP, Pinawa (Canada)	LHHPC and 40/60 BSM in granite	~5 m diameter, ~6 m height	2009 - 2020	Dixon et al. 2009 Martino & Kaatz 2010 Martino et al. 2011 Priyanto et al. 2016 Dixon et al. 2019
IB Blind Shaft test, Morsleben (Germany)	Gravel and asphalt in salt	~3.4 m square, ~6 m height	2015	Stielow et al. 2016
RESEAL, Hades URL (Belgium)	Bentonite clay between concrete units, in Boom clay	~2.2 m dia., ~3.4 m long	1996-2005	Van Geet et al. 2005

The ESP refers to the Enhanced Sealing Project, which is a shaft seal component installed during decommissioning of AECL’s Underground Research Laboratory (URL) in Manitoba. Part of the decommissioning activities was the placement of an instrumented shaft seal at the intersection of the URL access shaft with Fracture Zone 2 (FZ2) (Figure 8-5). The primary purpose of these seals is to isolate the near-surface groundwater flow systems from deeper, saline groundwater (Dixon et al. 2009).

The installed shaft seal, as seen in Figure 8-5, consists of a lower, reinforced LHHPC structural support component, a 40:60 clay-sand mixture, and an upper concrete component that restricts expansion of the clay component. This shaft seal was monitored for strain, temperature and hydraulic pressure in the concrete components, and water content, pore pressure, total pressure and temperature in the clay component. The hydraulic pressures monitored above, within and below the concrete restraint structures have indicated that the shaft seal has developed sufficient confinement within the clay based sealing component to effectively isolate the upper and lower shaft sections. The structure has also remained physically stable in its installed location. Remote monitoring will continue until 2020, at which point the remaining instruments are not considered to be reliable. Documentation of the seal construction and monitoring results are provided in Dixon et al. (2009), Martino and Kaatz (2010), Martino et al. (2011), Priyanto et al. (2016) and Dixon et al. (2019).

Working within shafts poses operational and safety considerations that need to be considered as part of closure design. Examples of some of the challenges involved are described in reports associated with the ESP construction (Dixon et al. 2009; Martino et al. 2011).

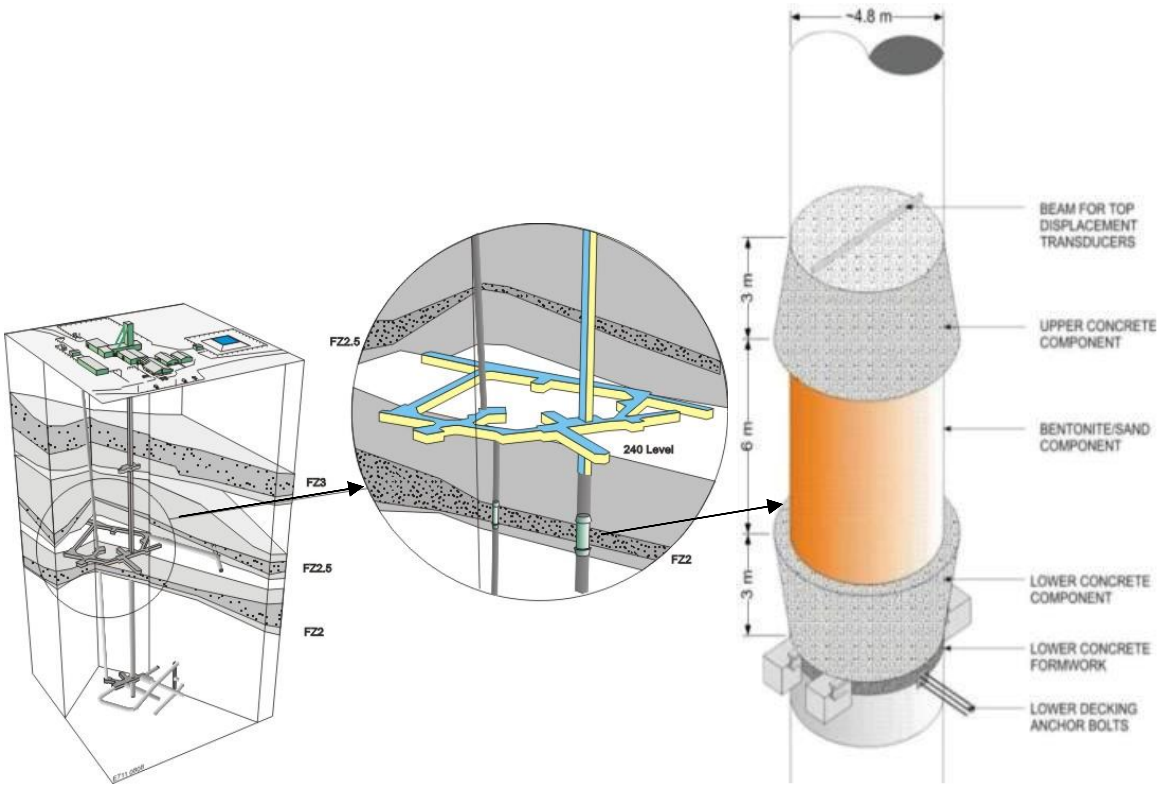


Figure 8-5: Location of the URL Shaft Seals and Design

At Morsleben, a mixed gravel and hot asphalt seal was installed within a salt rock shaft (Stielow et al. 2016). The primary purpose was to test installation methods, in particular related to the delivery of hot asphalt into a shaft. The test results showed that the seal was built as designed.

NWMO will continue to monitor international shaft seal performance projects, as well as continue to conduct basic materials testing and improve our ability for long-term chemical modelling. Once underground at the repository site, one project planned for the UDF will be a shaft seal test, which will be a long term-medium-scale test of the planned repository shaft seal materials in ground conditions at the site.

8.3.3 Borehole Seals

Deep monitoring and site investigation boreholes will be sealed to inhibit groundwater movement and contaminant transport along the borehole. Sealing of boreholes is commonly practiced in the construction and resource industries to decommission water, oil and monitoring wells. However the repository boreholes are generally expected to have higher requirements regarding permeability and durability than current industry practice.

Repository boreholes are generally expected to be filled with a combination of materials, depending on the specific borehole characteristics (Karvonen 2014; NWMO 2015; AMEC FW 2018; Sandén et al. 2018). Cement-based sealing materials are generally proposed to isolate fractured, permeable zones because of their low hydraulic conductivities and their groundwater resistance. For very low permeability over the long-term, bentonite-based materials are preferred, placed in bulk rock zones away from fractures. These may be supplemented and mechanically supported by filling with sand or aggregate in some sections.

A key practical issue is how to place dense bentonite at required depths while ensuring low permeability. SKB has explored placing bentonite as dense material in perforated copper piping sections (Karvonen et al. 2015), and also copper expanders that are placed in the borehole to separate material layers (e.g. cement from bentonite) (Sandén et al. 2018). A recent UK review (AMEC FW 2018) noted that bentonite can be placed as single-sized pellets, but recommended studies on whether and how bentonite pellets in a range of sizes could be emplaced to get higher density than achievable with single-sized pellets alone.

The materials and methods that can be used to design borehole sealing systems for sedimentary and crystalline rock host media have been investigated and generic design approaches developed that have direct application to NWMO's DGR. Borehole sealing design will be site specific and will need to deal with the unique sequence of geologic features present in each borehole. No specific fundamental development of borehole seals is presently planned by the NWMO. Practical experience in tests and in operation of URLs and mines will be reviewed, and used to focus NWMO planning and design in advance of construction of its repository.

8.4 Research Program Summary

Siting and Site Characterization Phase

Work continues to optimize the seal materials and to further characterize their properties. This will include measurements of physical properties such as mechanical strength and transport properties such as hydraulic conductivity and sorption.

NWMO continues to monitor developments in the long-term performance of seals by participation in sealing demonstration projects such as the Enhanced Sealing Project and GAST.

In the near term, further laboratory and field tests on compatibility of seal materials will be initiated.

Long-term geochemical and geomechanical evolution of the shaft seals will be studied through numerical modelling. This modelling can also be used to interpret the laboratory tests.

Site Preparation and Construction Phase

Activities planned for siting and site characterization will continue. Based on the findings of testing and modelling, a plan for in-situ demonstration will be developed.

Operations, Monitoring and Closure Phase

In-situ demonstration will be carried out at the UDF. Further optimization and characterizaiton of shaft seal design and seal materials may be required. Based on the demonstration findings and safety case requirements, the shaft seal design will be finalized and implemented as part of the repository decommissioning and closure.

Major Facilities

No major facilities have been identified for furthering the study of seal optimization, properties, and long-term performance demonstration.

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9 GEOSPHERE PROPERTIES

A comprehensive understanding of the properties of the geosphere at a potential repository site will be developed from information collected through several phases of assessments, which began with desktop studies (e.g. NWMO 2013a,b; 2014a,b). As potentially suitable repository areas are identified, preliminary geoscientific site investigations are initiated. As potentially suitable sites advance to borehole drilling, site-specific geoscience site characterization plans are developed. Geoscientific characterization of each site will follow the site-specific geoscience site characterization plan, and is not covered in this technical research program. The geoscientific characterization plan for a candidate site is designed to ensure collection of all relevant and required data to develop and evaluate the safety case. This includes the development of a site model (Descriptive Geosphere Site Model - DGSM) and a Geosynthesis based on the geosphere properties determined during the site characterization work.

Geoscience research supports the site selection and characterization processes and the development of the safety case, in an iterative and integrated manner. Advancing scientific understanding of the safety attributes of crystalline and sedimentary rocks currently being considered as potential host rocks is achieved through research designed to:

- Develop methods for characterizing the properties or attributes of a site (this Section);
- Reduce uncertainty with respect to the long-term evolution and stability of the geosphere environments (sedimentary or crystalline) potentially hosting a repository (see Section 10, Long-term Evolution).

The content of this section is organized as follows:

- Geological setting and structure;
- Hydrogeological properties;
- Hydrogeochemical properties;
- Transport properties of the rock matrix; and
- Geomechanical and thermal properties.

9.1 Geological Setting and Structure

The specialized methods required to characterize the geological setting at a potential repository site, including lithology, natural resources, bedrock petrography and mineralogy are well-established, although research to further refine and optimize particular methods may be on-going (e.g. geophysical techniques which are heavily reliant on technology and as such, will continue to evolve and improve). Established methods are being applied as part of preliminary assessments during site selection in both sedimentary and crystalline rocks. For example, NWMO Phase 2 Preliminary Assessments in crystalline rocks (e.g. NWMO 2015a, NWMO 2017a) have included:

- acquiring high resolution geophysical (magnetic and gravity) data to better understand the bedrock geology (geological contacts, depth and extent of rock units, and lithological and structural heterogeneity);
- detailed interpretation of surficial and magnetic lineaments to identify possible structural features such as fractures/fracture zones, shear zones and dykes;

- preliminary geological field mapping to confirm geological characteristics including lithology, structures and bedrock exposures; and
- high resolution LiDAR surveys to provide an accurate, high-resolution, bare-earth Digital Elevation Model (DEM) of the proposed area, which will serve as an important element of the DGSM for a specific site and provide definitive surface boundary conditions for watershed-scale groundwater system analysis. (Digital Surface Model, Contours and Hillshade representation of the surfaces are also produced from the LiDAR survey results.)

A particular area of interest to NWMO currently is Object-based Image Analysis for automated discovery of outcrops, as a tool to more efficiently and effectively plan geological mapping activities. A pilot study is planned to develop a protocol and demonstrate the approach, which if successful, could be applied as part of detailed site characterization activities at a crystalline site.

As part of site investigations, a DGSM will be developed for specific sites, summarizing the understanding of the geosphere characteristics at surface and within the subsurface relevant to repository engineering and safety assessment. The foundation of a DSGM is the geological model, which describes the 3D distribution of geological domains and the occurrence of discrete structural features. The site-specific geological model provides a basis for the geoscientific understanding of the site, its past evolution and likely future, natural evolution over the period of interest for safety assessment. For crystalline sites, this descriptive geological model is developed through the site investigations programs, using regional and site specific information.

For the sedimentary rocks in southern Ontario, a regional-scale three-dimensional geological and hydrogeological model has been developed (Carter et al. 2017). In 2019, NWMO launched a new research project in collaboration with the Geological Survey of Canada to support further development and refinements to this 3D geological model. Two important objectives of this work are to: i) reduce uncertainty in extents/geometry (thickness and occurrence) of formations in the 3D geological model of southern Ontario by QA/QC improvements to formation top records; and ii) incorporate regional faults in the 3D lithostratigraphic model to more accurately represent continuity/discontinuity of bedrock layers, relationships to hydrocarbon traps, and potential locations for cross-formational flow of groundwater and hydrothermal dolomite features. As part of this program, the 3D geological model will be provided to NWMO for use as the framework for the DGSM at a sedimentary site, which will further developed and refined with site-specific data.

In subsequent stages of site characterization, borehole drilling and other methods, such as 2D seismic surveys, are used to further characterize a potential repository site. Research areas of interest or particular focus, in the context of ensuring readiness and capacity for detailed site characterization and beyond, are described in the following sections.

9.1.1 Geophysical Site Characterization Methods

Airborne and surface-based, non-intrusive geophysical methods are commonly used to assess, relatively rapidly and cost-effectively, numerous geoscientific characteristics of interest.

A state-of-the-science review on satellite, airborne and surface-based, non-intrusive geophysical site characterization methods that could be used during the initial phases of the siting process was completed in 2008 (Emsley et al. 2008, Table 6.1). This review allowed the

NWMO to make informed decisions when selecting the methods for initial site assessments. The review included the geoscientific characteristics that could be assessed, the method accuracy, limitations and constraints, applicability to sedimentary and crystalline formations, commercial availability in Canada, survey time scales, and strengths and weaknesses of each method. The study included a review of key elements to be considered during survey design and also the geophysical methods and techniques that have been used in similar site characterisation programs in other countries.

In order to further develop readiness for detailed site characterization, a report reviewing available borehole-based geophysical tools and techniques for characterizing repository candidate sites was prepared (Monier-Williams et al. 2009). The borehole applications considered included: determination of lithology and stratigraphy, physical properties, rock structure and hydrogeological properties, in situ stress investigations and well inspections. The report evaluated borehole tool applicability, accuracy, limitations and constraints, and best practices. Nine studies were discussed, including case studies in both crystalline and sedimentary rock environments in Europe and North America. The techniques considered include: wireline tools (orientation, electric, induction, nuclear, caliper, imaging, gravity and nuclear magnetic resonance logs); flow logging tools (impeller, heat pulse, electromagnetic, and fluid (electrical conductivity) tracking); seismic methods (sonic and full waveform, tomography, reflection and vertical seismic profile surveys); borehole radar; and borehole time domain electromagnetic surveys and cross-hole electromagnetic surveys.

The reviews indicated that geophysical methods are well established. Several of these techniques have already been employed as part of the NWMO preliminary assessments for site selection. No additional research and development of these methods is currently planned. However, NWMO continues to monitor industry best-practice and available literature, including publications on recent site characterization activities in other countries (e.g. 3D seismic surveys completed by Nagra in Switzerland (e.g. Nagra 2019). NWMO also participates in projects at international URLs, in order to maintain awareness of advances in geophysical measurement technologies and new data collection and interpretive techniques. NWMO is particularly interested in developments in the following areas:

- New approaches to estimate rock properties (e.g. density, porosity) from seismic profiles, using correlations between 2D or 3D seismic survey profiles collected on surface and vertical seismic profiles within boreholes; and

- Potential applications for new satellite or area sensors (e.g. drones with sensors for hyperspectral imagining, gamma spectral, or radar sensors) for interpretation of rock composition or other properties.

9.1.2 Fractures/Fracture Zones, Faults and Joints

Characterization of fractures/fracture zones, faults, and joints is an important aspect to any repository site, but particularly in a crystalline rock site. The presence and distribution of fractures, in particular the hydraulic fracture network, in the geosphere strongly influences groundwater system dynamics and evolution. The predominant pathway for solute migration in crystalline rock is through the interconnected network of potentially permeable fractures.

9.1.2.1 Investigation Methods

Historically within the research program, an interpretative and systematic GIS based lineament analysis of the Whiteshell Research Area (WRA) was conducted using historic and remotely sensed data sets. The study explored the application of laser altimetry (LiDAR) to aid in surface based site characterization and lineament interpretation (Sikorsky et al. 2002a,b; 2003; Srivastava 2002a). Given that methods required for site characterization such as surface-based and borehole measurement techniques, including geophysical methods and geological mapping, are well-established, NWMO does not currently have any research programs underway on this topic. However, NWMO is monitoring industry best practice and the available literature for new developments in the following areas:

- Methodologies or approaches to reconcile differences between the features measured at different scales (e.g. fracture zones from lineament studies at kilometer scale versus fractures measurement in borehole at centimeter to meter scale), particularly in crystalline rock.

- Emerging technologies such as geoelectrical methods (including self-potential, electrical resistivity, and induced polarization), which may have potential for mapping of water-bearing fractures and/or fracture zones.

For example, in the preliminary assessment stage for candidate areas in crystalline rocks, regional airborne geophysical data, including high-resolution magnetic and gravimetric data are acquired, processed, and interpreted (e.g. NWMO 2015b; NWMO 2017b,c). This geophysical information is then used to interpret various features of bedrock units, in particular: i) geometry and thickness; ii) nature of geological contacts; iii) bedrock lithologies; degree of geological heterogeneity; and iv) the nature of structural features (e.g. faults, shear zones, or alteration zones). High-resolution airborne magnetic data is combined with topographic data (e.g. LiDAR) and high-resolution satellite image data to provide an updated interpretation of the geological and structural characteristics of the bedrock (surface lineaments, e.g. NWMO 2015c; NWMO 2017d,e).

Detailed geological mapping is also completed through site investigations during the preliminary assessments, with an emphasis on bedrock structure and lithology. As described in the previous section, further site-specific investigations include high resolution LiDAR surveys, borehole drilling, in-situ testing and sampling within the borehole, and laboratory analyses of core, to further understand the structural and lithological character of the bedrock at depth, as well as other properties; 2D seismic surveys and Vertical Seismic Profiling (VSP) within boreholes will also be conducted. These activities are described in the site characterization plans for each specific site.

9.1.2.2 Numerical Methods – Discrete Fracture Networks

For several years, the NWMO has been developing the ability to apply statistical methods to extend lineaments observed during surface based-studies to depth, including the ability to consider a range of uncertainty. The intent is to have structurally possible, geostatistically representative fracture networks that are directly derived from field data. Initially, these discrete fracture network (DFN) models are used to build an initial conceptual understanding of, and to visualize in three dimensions, the structures below surface at a specific site. As additional site-specific information is collected, and direct data on the presence (or absence) of structures is obtained (e.g. through borehole drilling), the site-specific fracture network model is progressively refined. The DFN models are, in turn, incorporated into i) numerical groundwater flow and transport models; ii) geomechanical models to examine the long-term stability of underground openings; and to inform repository design (e.g. layout, degree-of-utilization).

Initially, illustrative DFN models were created using software known as FXSIM3D for the Whiteshell Research Area (Srivastava 2002a), the Sub-regional Shield Flow System case study (Srivastava 2002b, Srivastava 2003, Srivastava et al. 2004), and for conceptual safety case studies (e.g., NWMO 2012, NWMO 2017). The fracture modelling procedure was also validated based on quarry field data from Lägerdorf, Germany (Srivastava and Frykman 2006). Most recently, together with MIRARCO and the Centre for Excellence in Mining Innovation (CEMI), NWMO developed a new version of the code, referred to as MoFrac (Bastola et al. 2015). This was required to further facilitate code development and testing by ensuring the code is available to a wide variety of potential users in the natural resource industries, in addition to nuclear waste management organizations.

A validation study for version MoFrac 2.0 of the software was conducted (Bastola et al. 2015). This study focused on several specific features of the generated DFNs: 1) fracture shape and undulation, 2) fracture orientation, 3) fracture intensity, 4) fracture traces, 5) fracture truncation rules, 6) fracture joining, and 7) regions. In Figure 9-1, example results for validation performed using data from the Hyposite NE tunnel are presented. The study concluded that MoFrac 2.0 produces DFNs that conformed to the input parameters, with a few, noted limitations (Bastola et al. 2015), and that MoFrac 2.0 can be used to generate DFN models incorporating field mapping data from underground excavations.

MoFrac is capable of creating DFN models at the tunnel-, site- and regional scale (e.g. Bastola et al. 2015; Junkin et al. 2017, 2018, 2019a, 2019b). Version 3.0 of MoFrac is currently being used within the site investigations program. This version of the code was validated using the same data set as Strivastava (2002b), to demonstrate the ability of the code to generate DFNs from surface-based data.

In parallel to MoFrac use in site characterization activities, further development and refinements to MoFrac are conducted through the research program. This enables model development and validation to occur in an iterative manner to support site characterization activities. In 2019, work commenced to develop version 4.0 of the code. Two examples of key development tasks were chosen to further advance the code for application to additional site-specific information as it becomes available are:

- Fracture branching and clustering: Fracture branching will permit MoFrac to simulate either branching or coalescing fractures. Fracture clustering will allow for control of the spatial distribution of fractures.

- Time slicing: Time slicing will be used to propagate multiple fractures simultaneously. Propagation will no longer be a whole-fracture process, but instead will operate on extending a partially-complete-fracture mesh.

Other capabilities that are proposed for future versions of the code include: i) the ability to import topography data (Digital Elevation Model) which can be used to define ground surface; ii) ability to allow region definitions in MoFrac using irregular geometries; and iii) ability to allow conditioning data for MoFrac to include mapped fracture intensities in a borehole. As part of

MoFrac development activities, additional metrics for verification and validation will be defined as new capabilities are added.

It is envisioned that MoFrac development will continue through the research program, in parallel with the site investigations program through to detailed site characterization. Once construction of the underground facilities begins, MoFrac will be used to generate tunnel-scale DFNs to capture real-time information from mapping of tunnel faces and further calibrate the DFNs during excavation.

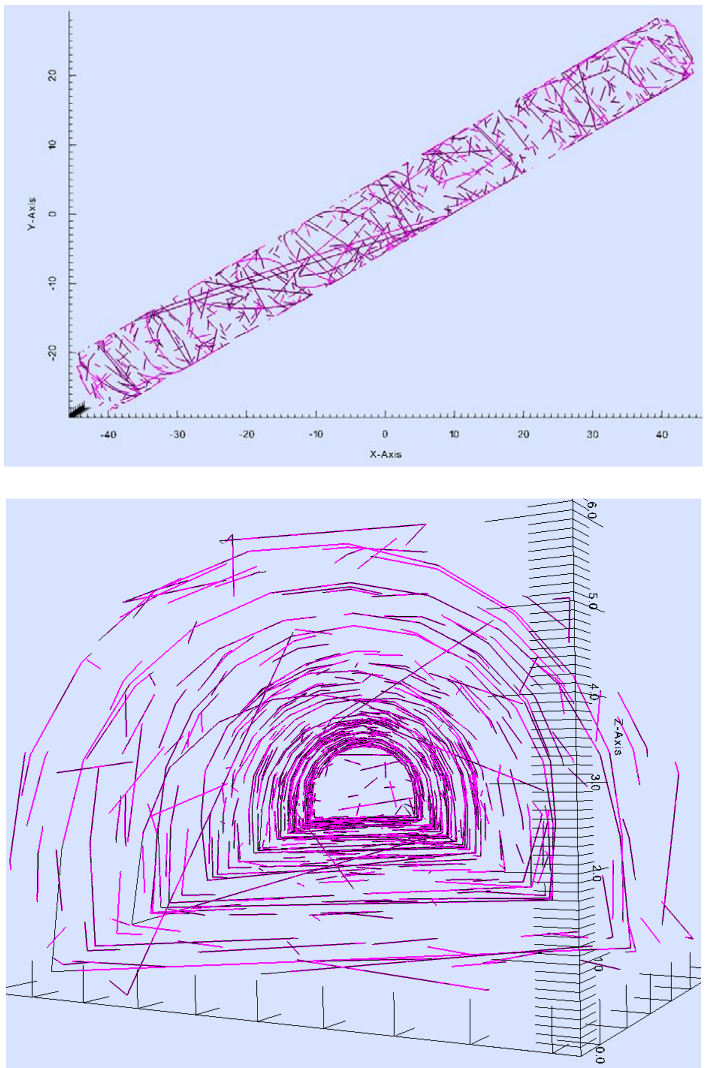

Figure 9-1: Comparison of input fracture traces (black) with output fracture traces (pink) in the Hyposite NE tunnel: (a) plan view, (b) cross-sectional view (from Bastola et al. 2015)

9.1.3 Metamorphic, Hydrothermal and Diagenetic Alteration

An understanding of the geochemical evolution of the proposed host rocks can be developed by examining evidence for the types of fluids (including their chemical composition and temperature) which have interacted with the rocks in the past. Examination of both fracture mineral infillings (where present) and alteration within intact rock directly adjacent to fractures can provide information on geochemical evolution. In a sedimentary setting, this includes changes which may have occurred during compaction and consolidation or diagenesis of the original sediments, and/or as a result of ingress of hydrothermal or meteoric fluids. In a crystalline setting, evidence of changes to the rock may be a result of interaction with fluids associated with different stages of metamorphism, or other hydrothermal fluids. In both sedimentary and crystalline environments, information on the timing of alteration, in particular for emplacement of infilling minerals in fractures, can be gained by geochronological methods. Furthermore, information on the chemical composition of these fluids which interacted with the rocks in the past are potential end-members to be considered when assessing the geochemical changes in the system that formed the porewaters presently observed within the rocks.

The NWMO has sponsored research on methods to characterize fractures, as well as on applying methods to develop an understanding of the regional geological history in Ontario to help understand site specific features. More recent activities are described below.

9.1.4 Diagenetic Alteration of Sedimentary Formations

Throughout the Paleozoic sequence in southern Ontario, laterally extensive carbonate formations occur, including Cambrian mixed carbonate-siliciclastics, Ordovician carbonates, Silurian carbonate-evaporite sequences and Devonian carbonates. Initially, petrological and geochemical research was undertaken by the University of Windsor into the occurrence of strata-bound dolomite layers within the Ordovician and Cambrian formations at a proposed site for Low and Intermediate Level nuclear waste at the Bruce nuclear site near Tiverton, Ontario (Al-Aasm and Crowe 2018). Dolomitization occurs when limestone ($CaCO_3$) is progressively changed to dolomite ($MgCO_3$). Dolomitization can occur in a broad range of geological environments and by different geochemical processes including: a) sabkha-type, b) mixed-water aquifer, c) seepage reflux, d) burial compaction, and e) hydrothermal.

The initial investigation demonstrated a lack of evidence for the presence of fault-related dolomites at this local, site scale. A similar study on a regional scale was then conducted to determine if the dolomitizing conditions observed within the Black River Group at the Bruce nuclear site are consistent across the Huron Domain. Core samples from multiple deep boreholes within the Huron Domain were analyzed for petrographic, stable and Sr isotopic composition, fluid inclusion microthermometry and major and trace elements to characterize diagenetic history, fluid composition and sedimentary provenance. In the current phase of research, rare earth elements (REE) are also being analyzed.

Data from the Cambrian and Ordovician formations across the Huron Domain suggest two possibly isolated diagenetic fluid systems: i) an earlier fluid system that is characterized by a pronounced negative shift in oxygen and carbon isotopic composition, more radiogenic ratios, warm (84-156^{o}C for dolomite and 87-141^{o}C for calcite;) and saline signature; and ii) a later Ordovician system, characterized by less negative shifts in oxygen and carbon isotopes, hypersaline, fluids of similar temperatures, and a less radiogenic fluid system. Generally, the results of this study indicate that diagenesis within Ordovician is horizontally uniform throughout the Huron domain.

This research will form the basis to develop an approach for collection and interpretation of data in sedimentary settings through detailed site characterization.

9.1.5 Metamorphic or Hydrothermal Alteration in Crystalline Rocks

The understanding of metamorphism in Precambrian rocks across the Canadian Shield was reviewed and summarized in NWMO (2013a,b). In 2019, a new research program was initiated in collaboration with Lakehead University to advance understanding of later stages of metamorphic or hydrothermal alteration within crystalline rocks of the Wabigoon Subprovince at a regional scale in northern Ontario. Minerals such as chlorite, epidote and silica mineralization associated with shear and fracture zones, and areas that have undergone ductile deformation as a result of regional metamorphism, will be investigated. A unique aspect of this research is that it proposes to study metamorphism and deformation in the granitoids of the Wabigoon Subprovince considering both hydrothermal mineral assemblages and structural features to better understand the regional geological history.

Studies have shown that hydrothermal alterations of granitoids can form micropores through a series of partial mineral dissolution, which in turn furthers the infiltration and progress of the alteration (e.g. Nishimoto and Yoshida 2010; Sadoon et al. 2011). The overall mass transfer between mineral components during the alteration can be calculated (Yuguchi et al. 2019). This information can be complemented with O and H isotopic signatures of chlorite or epidote (Petts et al. 2012), as well as chlorite thermometry. This information in turn, can be used to compare the environments in which mineral formation occurred, and to determine the origin of the fluids involved (e.g. magmatic or hydrothermal).

This research directly supports a parallel, site-specific study being conducted through the site investigations program. The regional information obtained from the research supports the site-specific studies and the geosynthesis for specific sites. It is anticipated that this type of research will continue at least through detailed site characterization.

9.1.6 Fracture Mineralogy

In both crystalline and sedimentary rocks, the minerals within fractures, and their openings (e.g., veins and vugs) provide information on the history of the rock mass in the geologic past. Vein and vug emplacement may be related to diagenesis (in sedimentary rocks), orogenic activity and/or past geologic uplift and erosion. Characterization of the secondary fracture mineral infill age, mineralogy, layering, and fluid inclusions can provide evidence related to fracture age, episodic fluid movement within the fracture and the composition of fracture fluids at the time of deposition. This information, in turn, provides evidence for the long-term stability of the system at timeframes of 1 Ma or greater, required to support the safety case for a repository site.

As part of the broader study of fracture characterization, research on the application of radiometric Uranium-Lead (U-Pb) age analysis of vein calcite was undertaken at the University of Toronto. A robust methodology was demonstrated to extract absolute ages of calcite mineral growth using a comparative analysis of Laser Ablation-Inductively Coupled Mass Spectrometry (LA-ICPMS) and Isotope Dilution-Thermal Ionization Mass Spectrometry (ID-TIMS) techniques

(Davis 2013; 2016). Results from these studies show that the shallow stratigraphic levels (Devonian-Upper Silurian) preserve approximately 110 to near 0 Ma old secondary calcite. The youngest examples are located in proximity to a regional unconformity, at the top of the Upper Silurian Bass Islands Formation, which is part of a near-surface permeable carbonate aquifer system influenced repeatedly by glacial events during the latter half of the Pleistocene. A sample from the deepest Upper Silurian Salina A1 Unit yields a ca. 318 +/- 10 Ma calcite age. Rare datable calcite veins in Ordovician (Trenton and Black River groups) samples only record syn-depositional to diagenetic Paleozoic ages (451 +/- 38 Ma and 468 +/- 25 Ma).

The U-Pb method for age dating of fracture calcites and for fluid inclusion studies are well established, as documented above. A summary of absolute and relative dating methods potentially applicable to fracture infilling minerals is given by Tullborg et al. (2001). A key finding from this study was the importance of understanding structural controls on fracture infilling minerals, and integration of all available geological data when choosing dating methods. Tillberg et al. (2017) is an example of an study where Rb-Sr dating has been applied in-situ to fracture mineralization. In general, the NWMO will maintain a capability in this area to continue to support or improve our understanding of the broader regional geological setting. The analyses will become more focused on the rock in and around the candidate sites, through detailed site characterization and geoscientific verification activities during construction.

9.1.7 Fracture Reactivation

Within the research program, Apatite Fission Track (AFT) thermochronology was initially applied to investigate regional basement reactivation and fracture propagation within the Canadian Shield. Precambrian-aged samples were obtained from the exposed Precambrian Shield of western Ontario and southeastern Manitoba, and beneath the Paleozoic sedimentary sequence of the Western Canada Sedimentary Basin. A suite of 10 samples from the Underground Research Laboratory (URL), located within the Lac du Bonnet Batholith in southeastern Manitoba, representing a 1100 m structural section through the batholith exposed by the URL and in sub-surface boreholes. The focus of the study was on applying AFT thermochronology to define the Phanerozoic thermal history of the samples (Everitt and Osadetz 2000). The study concluded that substantial fracture growth has not occurred to any significant degree after the Archean, in spite of repeated cycles of burial, uplift and erosion (Everitt and Osadetz 2000).

Through an international, collaborative project, the AFT analysis was then extended to the exposed Shield of eastern Ontario (Everitt et al. 2002). Based on analysis of 40 samples, the results indicate that the thermal history of the study area was subject to multiple episodes (i.e. late Precambrian, late Paleozoic and Tertiary events) of epeirogenic tectonism and crustal denudation on the North American craton of regional scale with uplift/subsidence cycles on the order of several kilometres. The most recent event identified was localized heating in the region east of Lake Nipissing, which is part of the Ottawa-Bonnechère rift system Jurassic-Cretaceous. However, the density of analyzed samples did not permit correlation with specific structures. Although the study area was subjected to repeated cycles of regional faulting and fracturing, uplift and downwarping and other events such as glaciation, significant areas of sparsely fractured rock continue to exist within the area studied (Everitt et al. 2002).

Within the Paleozoic succession of southern Ontario, burial-erosion estimates are presently based on a regional analysis of apatite fission track dating around the central portion of the Michigan Basin. Results suggest approximately 1.5 km of sediment were removed in the central portion of the basin, while at least 1.5-2 km of sediments were removed on the periphery in southern Ontario (AECOM and ITASCA CANADA, 2011). Indications of maximum burial depth have also considered the maturity of organic matter (e.g. NWMO 2011; Engelder 2011).

These methods could potentially be applied as part of a regional-scale studies to further understand the geological history and evolution surrounding the selected site (see also Section 10.1.3).

9.2 Hydrogeological Properties

9.2.1 Hydraulic Heads

The specialized techniques required to develop an understanding of the hydrogeological characteristics of crystalline and sedimentary rocks through site-specific studies – including measurements of hydraulic property distributions, hydraulic pressures and gradients, and hydraulic boundary conditions - are established and are being applied during site investigations as part of site selection. As the program moves into site characterization and then into construction and operation, the hydraulic head conditions around the site will be monitored. The measurements will be used in conjunction with modelling and other site properties (e.g. DFN) to demonstrate an understanding of the current conditions and the geological history leading to these conditions. This modelling will in turn inform paleohydrogeological modelling of future evolution at the site (Section 10.2).

The NWMO does not have on-going research in this area in terms of developing tools and methods for measurement of hydraulic heads. However, the NWMO continues to be involved in projects in which methods are applied. An example is the Long-term Pressure Monitoring Experiment (LP-A) completed at Mont Terri in 2018 (Ziefle et al. 2017). The aims of this experiment were to define issues for the long-term monitoring of pore parameters (pressure, temperature, water content, etc.), and to optimize the long-term monitoring of such parameters (e.g., frequency of acquisition, sensor type, duration of acquisition). Involvement in these types of experiments will continue to facilitate ultimately conducting these tests as part of testing at a specific site.

Tasks associated with interpretation of hydraulic pressures is an on-going area of research, particularly within the sedimentary rocks in southern Ontario where strong underpressures were observed during detailed site characterization activities at the Bruce nuclear site for a proposed Low and Intermediate Level Waste (L&ILW) repository (e.g. NWMO 2011). In low permeability rocks, hydraulic pressures are measured indirectly by inverse analysis of borehole hydraulic tests. An important task is to understand the uncertainties and potential measurement artifacts associated with inverse analysis. For measurements made within sedimentary rocks in southern Ontario, Beauheim (2013) examined errors, artifacts, and uncertainty in measured pressures, including i) leaks around packers, in system plumbing, in grout in the borehole and casing annulus; ii) dilation of rock into the borehole, and iii) coupled flows, such as chemical osmosis between formation and borehole. The study concluded that these were underpressures were real. On-going research into these underpressures in southern Ontario focuses on evaluating potential mechanisms which may have caused them – in other words, on understanding how these underpressures evolved over geologic time. This research is described in Section 10.2.1.

Through the research program, NWMO will continue to monitor industry best practice and available literature for new or improved measurement methods or approaches which could potentially be applied as part of site characterization or other research studies related to anomalous pressures which would support future geosynthesis activities.

9.2.2 Hydraulic Properties of Fractured Crystalline Rock

Historically within the research program, different approaches have been taken to increase understanding of hydraulic and transport properties of fractured crystalline rock at various scales, ranging from a single fracture to a sub-regional or regional scale. In the following discussion, several of these historic research programs are described, with a particular focus on the research conducted to understand groundwater flow and transport as it exists under present-day climatic conditions. An understanding of the paleohydrogeological conditions will be developed through site-specific measurements (Section 10.2.2) and paleohydrogeologic simulations to explore the stability of groundwater systems and potential changes to flow and solute transport under past and/or future climatic conditions are described in the next chapter (Section 10.2.1).

Atomic Energy of Canada Ltd. conducted detailed hydrogeological investigations in the Lac Du Bonnet Batholith at the site of the former Underground Research Laboratory (URL) in Pinawa, Manitoba. An extensive network of exploratory boreholes were drilled from surface and within the URL and tested to assess several major, shallow dipping fracture zones to depths of 1000m below surface (Davison and Kozak, 1988). A combination of single-hole straddle packer tests and large-scale interference tests within the boreholes in one of the zones (Fracture Zone 2) were used to assess permeability within the fracture zone. At a regional scale, permeabilities were observed to range over six orders of magnitude and form distinctive large-scale channel-like patterns which could be mapped for up to 1km in areal extent. At the local scale, permeabilities were observed to change over six orders of magnitude over distances of a few meters within the fracture zones. The measurements made at both the local scale and regional-scale illustrated the hydrogeological complexities that can exist within large fracture zones (Davison and Kozak 1988).

The Quarried Block Experiment was conducted to increase understanding of mass transport within a single natural fracture in granite and included both laboratory and numerical modelling activities. In a laboratory located at the 240 level of the former Underground Research Laboratory in Pinawa, Manitoba, flow and tracer experiments were conducted within a single, natural 1 m^2 fracture plane (with variable aperture). Numerical simulations of the experiments illustrated the complexity of flow and transport pathways through a well-characterized, heterogeneous, single fracture (Brush 2003).

The Moderately Fractured Rock (MFR) experiment was also undertaken at the 240 m level in Atomic Energy of Canada's (AECL) Underground Research Laboratory (URL) in an volume of rock on the order of 100,000 m^3 (for early results from these experiments see reports by Frost et al. 1998; Vandergraaf et al. 2001). In this experiment, forced gradient tracer tests were used to explore the applicability of the Equivalent Porous Media (EPM) approximation for simulation of solute transport in a fracture network at scales of 10 to 50 m. As part of the MFR experiment, analyses of a hydraulic interference test were made using the nSIGHTS code, developed by Sandia National Laboratories (Roberts 2002; Roberts and Domski 2005). This code was later applied as part of detailed site characterization activities for OPG's L&ILW DGR project (e.g. Intera 2011).

The primary objectives of the MFR experiment were to i) demonstrate flow and transport modelling capabilities, and ii) to test the hypothesis that solute transport through domains of moderately fractured rock (in which groundwater movement occurs through an interconnected network of discrete fractures) can be simulated as an equivalent porous medium (EPM) (e.g. Vandergraff et al. 2005; 2001; Chan et al. 2001; Frost et al. 1998). Numerical simulations using the EPM approach were performed using the code MOTIF, to develop a conceptual model of the MFR, incorporating geological zonation of the domain. An initial comparison of both the EPM and a DFN approach was also conducted using the code FRAC3DVS (Therrien and Lemieux 2002; Park et al. 2005), which is the code that eventually was developed into HydroGeoSphere (see Section 9.2.3). Park et al. (2005) demonstrated through calibration and validation results that a realistic geostatistical conceptualization of the hydraulic connections among the test boreholes could be developed for moderately fractured rock, and applied for predictive modelling with multiple stochastic realizations and careful error analysis.

Similar to the MFR experiment discussed above, the TRUE Block Scale project was performed at the Äspö Hard Rock Laboratory as an international collaboration between SKB, ANDRA, ENRESA, JNC, Nirex and Posiva (e.g. SKB 2002). The focus of the project was on site characterization and building of hydrostructural and microstructural models, sorbing tracer experiments in single structures and networks over distances between 15 to 100 m, and the application of various approaches to model the in-situ experiments. The major accomplishments of the project are documented in SKB (2002); Some examples are: i) demonstrated value of characterization techniques such as Posiva flow logs (PFL) to identify conducting intervals in boreholes; ii) the integrated network of characterization methods applied were shown to provide an adequate hydrostructural model at the block scale; iii) improved description of porosity and porosity distribution – in particular, new insight into the heterogeneous nature of flow paths within fault rock zones. Further refinements to the understanding of transport pathways at the block scale, including effects of geology, geometry and macro- and microstructure were attained during continuation projects and documented in SKB reports (e.g. SKB 2006, 2010a).

In order to develop a conceptual model of the geosphere for a potential repository site, an in-depth understanding of multi-disciplinary geoscientific information (geological, hydrogeological, geomechanical, geochemical, transport and thermal) must be acquired. Conceptual geosphere models are developed within an electronic database framework that facilitates the integration and interpretation of large and complex data sets. This framework improves traceability and communication of findings. A pilot project on the application of virtual reality technology in site characterization was conducted using data collected as part of the MFR experiment (Cotesta and Kaiser 2002; 2004). Following from the pilot study, Cotesta et al. (2004) applied these visualization tools to 3D stress modelling, in an illustrative case study of stress control on anisotropy in the permeability of the MFR experimental area. This study resulted in an improved understanding of how groundwater could move through the MFR experimental area by relating the existing fracture pathways with the contemporary stress field, and observations of the hydraulic responses.

Visualization tools will be used to integrate and interpret the multi-disciplinary data sets collected during site characterization activities to develop conceptual understanding and three dimensional numerical models of the sites. For example, numerical groundwater models are used as a means to assemble, integrate and illustrate the role of geosphere parameters and properties including topography, surface water features, fracture network models, and hydraulic conductivity distributions for both the rock mass and fracture zones. These geosphere models provide a quantitative framework to assess and illustrate the long-term behaviour of the groundwater systems at depth.

Within the research program, several studies involving numerical analyses of groundwater flow with regional (~5700 km^2) and sub-regional (~100 km^2) watersheds were conducted for crystalline rock using the code FRAC3DVS (Section 9.3.3) including Normani et al. (2003; 2007)), Sykes et al. (2003; 2004; 2009), Cornaton et al. (2008), Park et al. (2008; 2009). The hydrodynamic and geochemical stability of the deep groundwater systems was assessed by examining the influence of flow system dimensionality, spatial permeability distributions, discrete fracture network interconnectivity and salinity. Transient long-term boundary conditions were also investigated and are discussed in Section 10.2.1. The approaches and methods developed through this research were then applied in safety assessment case studies (e.g. NWMO 2012; 2017f). Normani and Sykes (2014) and Normani et al. (2014) published a methodology to incorporate realistic fracture zones into a groundwater model. These authors also conducted a comparison between a groundwater model which represents fracture zones as EPM with a model which incorporates discrete fracture zone networks. Differences in freshwater heads, total dissolved solids (TDS) and groundwater velocities in the discrete fracture zones were observed between the two approaches. The simulated TDS values at a given depth were lower when using the fracture zone approach, compared to the EPM approach, primarily due to the higher simulated velocities within the discrete fracture zones. Steady-state, density-independent simulations using both approaches produced similar freshwater heads.

As part of the preliminary assessments currently underway and continuing through detailed site characterization activities, the hydraulic properties of fractures and fracture zones will be determined in boreholes using specialized, established methods such as fluid flow (electrical conductivity) logging, and hydraulic packer testing. In later stages, as part of geoscientific verification activities during construction of the shaft and UDF, hydraulic interference tests may be conducted to further investigate the hydraulic properties of the rock mass and in particular, hydraulic connections between specific fractures or fracture zones (e.g. Posiva 2018; SKB 2019a). Such hydraulic interference tests could be conducted using boreholes drilled from surface during site characterization activities, or using a combination of boreholes drilled from surface and underground in the UDF (e.g. Posiva 2018; SKB 2019a). Geoscientific verification activities will be documented in a plan (Section 2.4.2), and will be used to further refine the Descriptive Geological Site Model (DGSM) originally developed as part of detailed site characterization activities.

Research at the University of Waterloo is currently focused on developing approaches to represent i) the variability in the 3D distribution of hydraulic properties (e.g. hydraulic conductivities) within the rock mass; and ii) heterogeneity of permeabilities within individual fractures as a function of depth (also called flow channelling or variability in aperture). Once developed, the approach for representing heterogeneous permeability within the rock mass and fracture zones will be used to define parameters for incorporation into site-scale and regional scale groundwater models being developed as part of site characterization programs. This research will continue in parallel with site characterization and its direction adjusted as required to meet the needs of the on-going site characterization activities and later, geoscientific verification activities.

Going forward, additional areas of interest within the research program are:

- Validation of site-scale DFNs (see also Section 9.1.2.2) and flow channelling (e.g. through SKB's GWFTS Äspö Task 10);
- Hydraulic tomography as a potential field method to characterize heterogeneities in hydraulic conductivity and specific storage in fractured rocks (e.g. Illman 2014) between boreholes (drilled from the surface and potentially also from within the UDF during geoscientific verification activities);
- New approaches to upscale brittle deformation zone flow and transport properties in crystalline rocks to achieve improved integration between geological and hydrogeological models (e.g. SKB 2019b);
- Methods to study groundwater flow through a combination of in situ measurements in boreholes and (non-intrusive) geophysical measurements; in particular, the potential usefulness of geophysical monitoring tools to correlate hydraulic properties/hydraulic conductivity distribution between boreholes (drilled from the surface and potentially also from within the UDF during geoscientific verification activities).
- New geophysical and/or chemical, isotopic, hydraulic and thermal field methods for identifying at ground surface the location of groundwater discharge zones within watersheds in crystalline rocks (e.g. Gleeson et al. 2009).

9.2.3 Numerical Methods – Groundwater

Within the research program, the numerical code FRAC3DVS (Therrien and Sudicky 1996) was applied to simulate steady-state or transient groundwater flow and advective-dispersive solute transport in discretely-fractured porous media (see Sections 9.2.1and 9.2.2). Over the years, enhancements to the original code were completed, including the development and implementation of a spatial sub-discretization methodology (Guvanasen 2005) and subgridding, hydromechanical deformation, and anisotropic molecular diffusion (Guvanasen 2007). This led to the development of FRAC3DVS_OPG, a version of the code specifically for application in Canadian nuclear waste management related activities, including both research and site investigations (Therrien et al. 2010).

The FRAC3DVS family of codes eventually were developed into the commercially available code, HydroGeoSphere (HGS, Aquanty Ltd.). Following a comparison and demonstration of the functionalities of HydroGeoSphere to FRAC3DVS_OPG, HydroGeoSphere was adopted by NWMO as the primary code for modelling of groundwater systems. This code is used in research, has been used in recent illustrative safety cases (e.g. NWMO 2018; 2017f), and is currently being used during the development of early conceptual groundwater models for specific sites involved in site selection.

Through the research program, NWMO is funding the development and verification of several new capabilities with HGS required by Geoscience and Safety Assessment (e.g. ability to map a fracture network generated in MoFrac to HGS for a particular element type; new capability to allow transport simulations to be conducted using pre-calculated steady-state flow field). This type of development work will continue to be supported through the research program through detailed site characterization activities and beyond, if the need for new or refined code capabilities are identified.

9.3 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 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.

Methods for the analysis of groundwater composition generally are well established in the scientific community and, provided sufficient groundwater can be collected, such methods are readily applicable in either field-laboratory or commercial-laboratory settings. These methods are already being applied in NWMO preliminary assessments and documented in site characterization plans. A significant area of research historically has been on development of techniques to extract porewater from the very low porosity 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 also continues to be an active area of research - due to the indirect nature of these extraction procedures, as described in the following sections.

9.3.1 Groundwater Composition

Various studies have indicated that the groundwater within the crystalline rocks of the Canadian Shield transition from a shallow, generally freshwater system, to a deeper, more saline system at a depth of a few hundred meters (Singer and Cheng 2002; Gascoyne 2000, 2004; Frape et al. 2004).

For example, within the Lac Du Bonnet granitic batholith in Manitoba, Gascoyne (2000) identified three flow systems:

- An active groundwater system in the upper ~200 m of fractured bedrock, with residence times of tens to hundreds of years;
- An intermediate system between 200 and 400 m containing fracture groundwaters with residence times of 10^3 to 10^5 years; and
- A deeper regime at depths of greater than 500 m with salinities up to 50 g/L and residence times of over 10^6 years.

More generally, the salinities of fluids sampled at depths of 500 m or greater from within crystalline rocks across Canada range between ~5 and 250 g/L (Frape et al. 2004).

In sedimentary rocks in southern Ontario, two hydrogeochemical systems have been identified at a regional scale (Hobbs et al. 2011):

- A shallow system (<200 m) containing fresh through brackish waters, with stable water ($\delta^{18}O$, $\delta^{2}H$) isotopic signatures consistent with mixing of dilute recent or cold-climate (glacial) waters with more saline waters;

- An intermediate to deep system (>200 m) containing brines associated with hydrocarbons in reservoirs which are characterized by high Total Dissolved Solids values (200 to 400 g/L). The stable hydrogen and oxygen signatures of these waters are typical of sedimentary basin brines in that they are enriched relative to the Global Meteoric Water Line).

Skuce et al. (2015) undertook a study to develop a geochemical tool to identify fluid sources in abandoned petroleum wells. To support this new tool, the authors built on the existing regional geochemical database by adding more samples and a larger suite of isotopes. Over 130 samples were collected from all major water-bearing units in the region. Considering this new data set, previously available data (e.g. Hobbs et al. 2011 and references therein) and information on groundwaters and porewaters from boreholes drilled as part of site characterization activities for a L&ILW repository in southern Ontario (Clark et al. 2013; Al et al. 2015), the transition zone between the brines and overlying meteoric water system is estimated to occur between ~200 and 450 m (Skuce et al. 2015), depending on the location within southern Ontario. As noted by Skuce et al. (2015), the meteoric water system and the underlying brines are hydrologically isolated from each other by the evaporates in the Salina Group, by the low topographic gradients in the region, the high density contrast between the water types and a general lack of discharge pathways for deep reservoirs.

Although methods for the analysis of groundwater composition are generally well established, characterization of the in situ sulphide or sulphate content of groundwaters (and porewaters), which is relevant to engineering/design considerations for the repository, is a more challenging task, and results may be impacted by oxidation processes during collection and/or preparation for analytics. Consequently, routine methods for characterization of the groundwater sulphur system may need to be adapted specifically for the low volumes of groundwater and low sulphur concentrations that are expected to be found at depth at a potential repository site. Within NWMO's research program, a state of science review is underway to review advances in sulphur analysis and identify techniques which could potentially be applied as part of site characterization (see also Section 9.3.2 below).

9.3.2 Microbial Characterization - Waters

Microbial communities have the potential to impact variables directly related to repository safety, such as radionuclide migration and corrosion of the used fuel containers; therefore, their characterization is a component of site investigation activities. Within the research program, a state of science review of international literature and knowledge on the role of microorganisms in relation to the key issues affecting the design and performance of a used fuel repository was completed by Sherwood Lollar (2011). This review of international programs demonstrated that the integration of microbiological characterization programs with geological, hydrological, and geochemical investigations to ensure feedback between these approaches. The review considered the relationships between environmental conditions within the deep subsurface (salinity, porosity, water activity, temperature, geochemistry) and microbial activity. A key finding in this regard was the presence, diversity and activity of indigenous microbial populations in the far-field is controlled by a number of factors, including principally: physical (geological) and chemical (including mineralogical) properties of the host rock; transport properties of the host rock; geochemistry of the associated groundwater; rock properties such as porosity, permeability, hydraulic conductivity and the presence and degree of inter-connections between fractures (especially important in crystalline rock); and the geological and geochemical history of a proposed repository site.

A particular topic of interest is sulphate-reducing bacteria (SRBs) because of their ability to produce sulphides, which can cause corrosion of the copper container. Lin et al. (2006) suggest that long-standing communities of SRBs are present in the deep fracture waters of the Canadian Shield, as has been demonstrated previously in crystalline systems of similar age in South Africa (e.g. Onstatt et al. 2006) and the Fennoscandian Shield (for a review see Pedersen 2000). The NWMO is currently funding a case study at Kidd Creek, a mine and underground research facility in a crystalline setting in Timmins, Ontario. The project involves development of isotopic techniques to evaluate biogeochemical processes. Using fluid samples from the Kidd Creek mine, stable carbon and hydrogen isotopic methods are being developed to evaluate the potential for methanogenesis *in situ*. Sulphate-reduction processes are also being assessed using sulphur isotopic approaches. This study will evaluate the merits of these analytical techniques for assessing sulphate-reducing bioprocesses in a low sulphide environment, similar to what is expected in sites engaged in the site selection process. Sampling and analytical protocols will be developed and documented in the final report.

Based on this information, new research programs will be developed to:

- Continue to refine our understanding of microbial processes and biogeochemical indicators in the deep subsurface and their potential to impact a DGR, through case studies and international collaborations;
- Continue to develop understanding of potential sources of sulphate and sulfide in crystalline rock settings in light of increasing recognition of the role of radiogenic water-rock reactions; and
- Assess the microorganisms present at Canadian repository sites, and their potential metabolic processes. Going forward, this work will move under the site assessment program to ensure integration with other hydrogeological, geochemical and geomechanical results.

9.3.3 Colloids in Groundwater

Colloids present in groundwater, or formed at the interface with the sealing systems (see Section 7.9.2 on bentonite erosion), may provide a mechanism for radionuclide transport in the geosphere. Degueldre et al. (2000) compared colloid concentrations from a variety of groundwaters and geological settings including granite, tuff, phonolite, marl and sandstone. This study concluded that, in general: i) colloids were found to be stable when alkaline element concentrations are below 10^{-2} mol/L and alkaline earth elements are below 10^{-4} mol/L; ii) colloid compositions are determined by the mineralogy of the aquifer (Granite: quartz, feldspar, biotite, clay; Sandstone: quartz, feldspar, clay; Marl: quartz, clay, calcite, organic); and iii) colloid concentrations are enhanced by transient conditions such as changes in flow, temperature and chemistry.

Available evidence shows that the concentrations of natural colloids are low in the Canadian Shield (Davison et al. 1994, p.337), but this would need to be confirmed for a specific site. Clay mineral colloids may be important in low salinity waters (Vilks and Miller 2006). In the sedimentary rocks of southern Ontario, where porewaters at repository depths are highly saline, colloids are not expected to be important.

In the past, NWMO's research program has supported laboratory scale experiments with SKB to investigate the potential for bentonite colloids originating from repository buffer materials to facilitate radionuclide transport in the geosphere (Vilks and Miller 2006; 2009; 2010). Current knowledge on clay colloids relevant to the long term safety case is summarized in Shelton et al. (2017). In general, bentonite colloid stability depends on the ionic strength (salinity) of the groundwater and the divalent ion content and, therefore, is dependent on the site groundwater chemistry and conditions.

NWMO will evaluate the importance of colloids during the detailed site characterization phase in the context of site specific information.

9.3.4 Porewater compositions

In both sedimentary and crystalline settings, an understanding of the porewater compositions within the pore space of the rock matrix can be derived from profiles of natural tracers (including dissolved ions and gases) collected from near the Earth's surface to depths below the repository horizon (e.g. Mazurek et al. 2011). These tracer profiles can provide insight on the history of fluid movement and on dominant transport mechanisms on time and space scales not otherwise achievable (e.g. Mazurek et al. 2009, 2011; Waber et al. 2009). In particular, stable water isotope ($\delta^{18}O$, $\delta^{2}H$) compositions of groundwaters and porewaters within low permeability, deep-seated groundwater system provides information on the stability and resilience to past glaciations. Significant challenges exist in the extraction and characterization of pore fluid from matrices of both sedimentary and crystalline rocks. These challenges are a result of the low water content due to low porosities (0.003 – 0.08 for sedimentary rocks in southern Ontario; ≥ 0.001 for crystalline rocks), and low permeabilities ($<10^{-18}$ m^2) of the rock matrices, and of the high ionic strengths (1-7 M) of porewaters present in the sedimentary rocks in southern Ontario, and which may also be present in crystalline rocks (Section 9.3.1).

For sedimentary rocks, several methods were previously investigated, including ultracentrifugation (Gascoyne and Hobbs 2009), isotope diffusive exchange (de Haller et al. 2016), micro-vacuum distillation, and crush-and-leach as part of site characterization activities for OPG's proposed L&ILW DGR project in southern Ontario (Clark et al. 2013; Al et al. 2015). Most recently, research was completed at the University of Bern, Switzerland to benchmark both sequential high pressure (>100 MPa) mechanical squeezing and the adapted isotope diffusion methods for porewater extraction and characterization (Rufer and Mazurek, 2018). The Advective Displacement Method has also been applied to the Opalinus Clay in Switzerland (e.g. Wersin et al. 2018). At the University of Ottawa, research continues on a novel technique that passively absorbs porewaters onto cellulose paper (Celejewski et al. 2014; 2018).

Research to understand the relative roles of bound and structural waters within clays on determination of porewater compositions is underway at Western University. At the University of New Brunswick, a new research program is underway as part of the NEA Clay Club "ClayWAT" project to investigate the potential application of Magnetic Resonance Imaging (MRI) techniques to examine the interaction of water and ions with clay mineral surfaces. Clay-rich rocks from Belgium, France, Switzerland, Hungary, Japan and Canada are being examined as part of this study.

In crystalline rocks, the common presence of saline fluid inclusions prevents the use of crush-and-leach techniques for porewater extraction. Alternative methods for determining porewater compositions in crystalline rocks are generally well developed, established in part through the Scandinavian waste management programs (e.g. Waber et al. 2013; Waber and Smellie 2012; Eichinger et al. 2010). These techniques were also applied through NWMO's research program to crystalline core drilled as part of the Greenland Analogue Project (Eichinger and Waber

2013). As part of recent site characterization activities at Olkiluoto, Finland, Eichinger et al. (2011) examined dissolved gases within porewater in the rock matrix, in addition to the chemical and isotopic composition of the porewater. This included an examination of both dissolved helium and hydrocarbon concentrations (methane, ethane, propane and butane) and ratios, and comparison to those in fluids trapped in fluid inclusions.

Building on the successful application of vacuum distillation techniques to sedimentary rocks, researchers at the University of Ottawa are developing and testing a method adapted for characterizing the stable water isotope composition ($\delta^{18}O$, $\delta^{2}H$) in crystalline rocks using heating and vacuum extraction of intact cores. Once the method has been demonstrated for cores saturated with waters of known isotopic composition, further experiments will be conducted to benchmark this adapted method against other existing methods.

Going forward, NWMO will continue to monitor industry best-practice and available literature for advances in techniques for porewater characterization, and to participate in projects at international URLs or other international collaborative projects, as opportunities permit. Particular areas of interest are: i) approaches for reconstructive geochemical and/or reactive transport modelling to provide bounding estimates of in-situ porewater composition; ii) methods for characterization of porewater gases; and iii) characterization of other fluids in crystalline and sedimentary systems which have been isolated over even longer time periods than porewaters. This includes fluids in the “unconnected” or disconnected/isolated pore spaces within the rock (e.g. fluid inclusions), because knowledge of the composition of these fluids is complimentary for interpretation of the paleohydrogeochemistry of the system (see also Section 10.2.2). These new and/or improved porewater characterization methods could be applied during detailed site characterization activities or to cores from boreholes drilled underground as part of geoscientific verification activities.

9.3.5 Microbial Characterization - Rocks

Techniques for the characterization of potential indigenous microbial communities in low-permeability sedimentary rock were developed through the research program using core samples from shale, interbedded shale and limestone, argillaceous dolostone and argillaceous limestone from southern Ontario (Slater et al. 2013). Traditional microbiological, molecular genetics and phospholipid fatty acid (PLFA) approaches were applied. The experimental and analytical approach developed was shown to be an effective means to assess low biomass systems, which will be used in planning future site investigations in sedimentary rock. An initial application of these methods to crystalline rocks is underway as part of site-specific investigation activities.

9.3.6 Mineralogical Evidence for Redox Conditions

Redox conditions in the groundwaters and porewaters at repository depths has important applications to assess the stability of the used fuel container (in particular, the copper coating), the mobility of radionuclides and to develop an understanding of the long-term geochemical stability of the deep geosphere.

In addition to redox measurements conducted on groundwater samples, mineralogical investigations are performed to identify evidence of redox conditions/redox fronts with depth (based on Fe, Mn oxyhydroxides with depth from surface within the rock matrix, as well as fracture infills). Earlier research in the Canadian program focused on the development of analytical TEM methods for paleoredox investigations (Cavé and Al 2005). Generally, methods for mineralogical investigations of paleoredox conditions are well-established, and were applied as part of site characterization activities conducted in crystalline rocks in Scandinavia (e.g. Drake and Sandström 2006). Similar mineralogical investigations were also completed through the research program as part of the Greenland Analogue Project (Claesson Liljedahl et al. 2016). The next application of these methods is expected at the selected site during detailed site characterization activities, and may also be incorporated into geoscientific verification activities in the UDF.

9.4 Transport Properties of the Rock Matrix

The transport properties of the rock matrix inform evaluations of solute and/or fluid transport relevant to safety assessments of radionuclide mobility and the long-term evolution of the geosphere. The key transport-relevant properties in both sedimentary and crystalline rocks are: porosity, permeability, diffusion coefficients, gas transport properties, and sorption.

The dominant transport mechanisms differ between sedimentary and crystalline rocks. In sedimentary rocks, the host formation normally has a limited thickness, typically 100 to 200 m (Mazurek 2017). The reference Canadian sedimentary rock formation is the low permeability, low porosity (total porosity 1-3%) argillaceous limestone of the Cobourg formation in southern Ontario, where transport occurs through the rock matrix primarily by diffusion (e.g. NWMO 2011).

In crystalline rocks, transport in fracture networks is the primary mechanism for groundwater flow and solute transport (e.g. Mazurek 2017). In the repository concept, waste will be placed in low-permeability host rock; consequently, transport properties of the sparsely fractured rock, and within the fractures are relevant. In these systems, mass transfer by diffusion from the water flowing in the fracture to the water within porosity of the rock matrix (matrix diffusion; Neretnieks 1980) may retard the transport of radionuclides to the surface.

Groundwater flow and solute transport within a fractured crystalline rock at different scales was discussed in Section 9.2.2. In the following sections, methods used to determine the physical and transport properties of the rock matrix are discussed.

In addition to on-going research activities, NWMO continues to monitor industry best practice and available literature for advances pertaining to in-situ measurements methods, which could be considered for application during geoscientific verification activities to be conducted within the UDF.

9.4.1 Porosity

Porosity is a general term used to describe the fraction of the volume of voids over the total rock volume. The main types of porosity measurements are total porosity (also referred to as physical porosity), liquid porosity (for rocks containing porewaters with high salinities), water-loss porosity, and connected porosity. In both sedimentary and crystalline rocks, laboratory methods are available for determining the different types of porosity. Total porosity is usually calculated based on bulk and grain density data. Water-loss porosity is typically determined gravimetrically through heating and drying of rock samples. Connected porosity can be determined using helium porosimetry applied to samples under confined or unconfined conditions.

Although crystalline rocks contain fracture networks, water within the low-porosity rock matrix is the main reservoir for water in the system and usually exceeds the amount of water present within fractures (Mazurek 2017). If this porosity within the rock matrix is connected (i.e. there are interconnections between the pore spaces), then the radionuclide concentrations in fracture water may be reduced by matrix diffusion. This connected porosity can provide access to the surface area of mineral surfaces, where sorption may occur. This is particularly difficult to assess using laboratory-based studies, where the porosity measured in core samples may be higher than the actual, in-situ porosity due to effects of stress release or microscale damage to the core during sample preparation.

As part of a study conducted to compare laboratory and field techniques for characterizing diffusion in the sparsely fractured granite of the Lac Du Bonnet batholith, Vilks et al. (2003; 2004, 2005) compared porosity values measured using laboratory experiments for samples taken from different depths within the Whiteshell underground research laboratory (see also Sections 9.4.2 and 9.4.3). The results showed a progressive increase in the measured porosity for samples removed from greater depths, and therefore, increasingly higher rock stress regimes. These results illustrate that rock samples removed from high stress conditions are altered by in-situ stress relaxation, and potentially also by stresses created during drilling (Vilks et al. 2005).

NWMO continues to monitor the scientific literature for new methods for determining porosity. A small literature study is underway to determine if there is an empirical relationship between effective diffusion coefficient (see Section 9.4.3) and diffusion-accessible porosity for crystalline rocks, as has been observed previously for sedimentary rocks. In-situ experiments to measure connected porosity, such as those conducted in crystalline rock at the Grimsel Test Site in Switzerland (e.g. Schild et al. 2001; Möri et al. 2003) are of particular interest. Any advances in-situ measurement methods, which may include a suite of complimentary laboratory measurements (e.g. Möri 2009), could then be considered for application during geoscientific verification activities during repository construction.

9.4.2 Permeability (Water and Gas)

Laboratory measurement methods for hydraulic conductivity and/or permeability of the rock matrix are relatively well-established and include both steady-state methods, which are applied to soils and rocks with higher permeability, and pulse-decay techniques applied to rocks with much lower permeability. During permeability measurements, the effects of scale, flow direction relative to fabric orientation, confining stress, temperature, and shear stress/strain (pertinent to damage in EDZ) must also be considered.

The pulse-decay permeability method was originally developed by Brace et al. (1968) for measurement of permeability of intact granites under high pressures. Laboratory permeability estimates of core samples from the Lac Du Bonnet batholith were made using a hollow core permeameter and a High Pressure Radionuclide Migration Apparatus (HPRM), which was used as a permeameter with a triaxial confining pressure to simulate lithostatic pressures of up to 17 MPa (Vilks et al. 2005). In-situ permeabilities were estimated from the analysis of shut-in hydraulic tests using the code nSIGHTS (Roberts 2003). This study demonstrated that laboratory measurements made without confining pressure resulted in higher permeability estimates than those made under confining pressures. Even under confined conditions, it was found that laboratory permeability estimates were a factor of 2 to 100 times higher than the in-situ permeabilities calculated from the hydraulic tests, as described above. This was attributed to alteration of the rock samples as a result of in-situ stress relaxation, and stresses created during drilling (Vilks et al. 2005).

In southern Ontario sedimentary rock, early estimates of the permeability of the Ordovician-aged shales and limestone formations were made using a High Pressure Radionuclide Migration Apparatus (Vilks and Miller 2007). As part of site characterization activities for OPG's proposed L&ILW DGR project , permeabilities of the Cobourg Formation to both gas and brine were measured in the laboratory using pulse-decay permeability tests (INTERA 2011). Through the research program, hydraulic pulse tests were used to measure the permeability of the Cobourg limestone under isotropic stresses up to 20 MPa. The overall permeability measured for the Cobourg ranged between 10^{-22} and 10^{-19} m^2 (Nasseri and Young 2014; Selvadurai 2017).

Selvadurai and Lowaki (2018) measured the local permeability within the Cobourg formation, including light grey limestone and dark grey argillaceous partings. It was found that the darker phase has a permeability that is approximately one order of magnitude greater than the lighter species. Research is currently underway at McGill University to estimate the overall permeability of the Cobourg based on the spatial distribution of these lighter and darker phases (Section 9.5.2). These estimates will be compared to the values measured using hydraulic pulse tests.

In the near term, pulse-decay techniques will be applied to determine the permeability of core collected from site-specific activities. In parallel, research is underway to investigate the effect of confining stress and scale (sample diameter up to 150 mm) on permeability measurements of the Lac du Bonnet granite, as an analogue for the crystalline rocks investigated through site selection. Comparison between steady-state and pulse-decay permeability testing results, as well as the evolution of permeability during progressive shearing (pertinent to EDZ), will also be investigated (see Section 9.5.2). The findings of this research will be used to inform the experimental conditions to be used during detailed site characterization.

9.4.3 Diffusion Properties

Within low permeability groundwater systems, contaminant mobility is primarily by diffusion. The determination of transport properties such as diffusion can be complicated given the low permeability of the rock matrix, the pore geometry and interconnectivity as influenced by pore fluid compositions and ionic strength, secondary mineral precipitation, anisotropy and ionic charge.

As part of the research program, measurements of diffusion properties in the crystalline rock of the Lac Du Bonnet batholith were conducted under laboratory and in-situ conditions within 10 m long boreholes within the Whiteshell underground research laboratory (Vilks and Miller 2002; Vilks et al. 2003; 2004; 2005). The tracers investigated included Br,I, Li, Rb and the organic dyes lissamine and uranine. It was found that laboratory-based diffusion coefficients for the deeper URL levels were higher than those determined in-situ by a factor as high as 15.

The development of laboratory protocols to characterize the mass-transport properties of sedimentary rock using steady-state diffusion cells (also referred as through-diffusion experiments) was originally undertaken by Vilks and Miller (2007). An X-ray computed tomography (micro-CT) radiographic technique for quantifying the concentration distribution of an iodide tracer solution in rock samples was developed at the University of New Brunswick to study diffusive transport and evolving reactivity in sedimentary rock. In 2008, samples of

Queenston shale and Cobourg limestone in Ontario were examined using both techniques (Cavé et al. 2009). Similar values for the effective diffusion coefficient (D_e) were obtained using both radiography and through-diffusion methods.

Further work on methods development at the University of Ottawa has continued on steady-state diffusion cells, out diffusion from rock cores, and the above micro-CT technique (Cavé et al. 2009, 2010; Agbogun et al. 2013; Xiang et al. 2013; Loomer et al. 2013). The main areas of study include; i) the influence of rock core relaxation and decompression on laboratory estimates of effective diffusion coefficients (D_e); ii) the impact of preferential diffusive pathways along mineral grain boundaries, microfractures and dolomitization on D_e; iii) influence of free gas (partial saturation) on D_e (Figure 9-2); iv) estimation of effective pore diffusion coefficients for tritiated water (HTO), ^{137}Cs and ^{90}Sr; and v) determination of apparent diffusion coefficients for CH_4, CO_2 and He (Xiang et al. 2016).

Most recently, NWMO supported research to conduct reactive transport simulations of in-situ diffusion experiments within sedimentary rock as part of the Mont Terri Project (Xie et al. 2014).

Considering the importance of diffusion-related processes in deep low-permeability environments, it is expected that there will be ongoing research to improve scientific understanding through to the operations and monitoring phase.

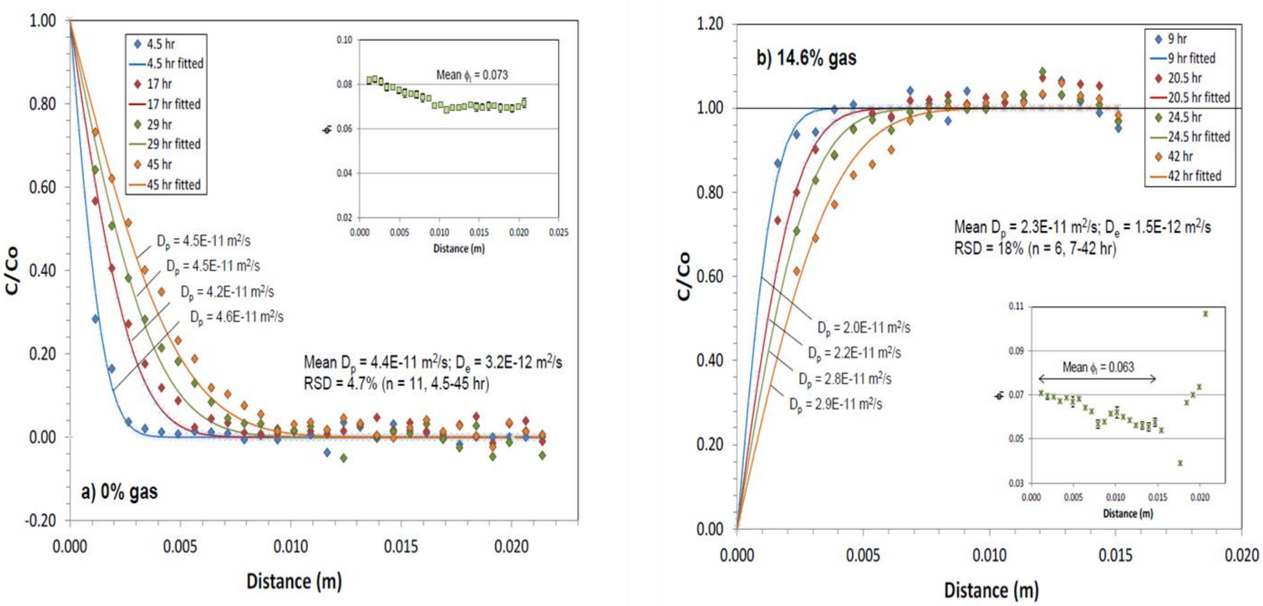

Figure 9-2: Tracer diffusion data for a) fully brine-saturated and b) partially brine-saturated samples of Queenston Formation shale. Note the 53% decrease in D_e for iodide that is observed for partially saturated conditions (14.6% gas, 85.4% brine).

9.4.4 Sorption

Sorption can be a significant factor in the retardation of radionuclides in the geosphere, but is more dependent on groundwater chemistry and flow path conditions (minerals, especially accessible surface area for radionuclides) than other transport processes.

Historical work on sorption of radionuclides on bentonite clay and granitic rocks was carried out in 1980s and 1990s as part of the AECL program, and furthered in Scandinavia. This provides a base set of information on the behaviour of radionuclides in other granite-like Canadian Shield rocks (Ticknor and Vandergraaf 1996; SKB 2010b).

The inclusion of sedimentary rock sites in the NWMO siting process led to a significant effort by NWMO over the past several years to develop a database of sorption properties for Canadian sedimentary rocks for a generic repository site (Vilks 2009; Vilks et al. 2011). In particular, the ability to conduct sorption measurements in these saline systems under reducing conditions has required method development. The database currently includes 28 elements for which sorption may be important to the DGR safety case (Vilks and Yang 2018). It compiles sorption data covered in the published literature through to 2017, and also includes in-house sorption measurements for 15 elements on sedimentary rocks of southern Ontario (Cobourg limestone, Queenston shale) and bentonite under saline conditions (e.g. Vilks et al. 2011; Vilks and Miller 2013; Bertetti 2016; Vilks and Miller 2018; Nagasaki 2018).

The NWMO program is shifting to develop sorption databases that are specific to the candidate siting areas. In particular, sorption experiments with rock core from candidate siting areas will be undertaken using representative synthetic groundwaters, which take into consideration the groundwater or porewater chemistry observed at site. This work is covered under the site characterization plan for each area. Concurrently, supporting work continues through the research program to i) develop methods and models for the behaviour of key elements;

ii) refine methodologies for converting measured sorption distribution coefficient (K_d) values on crushed rock samples to K_d values for intact rock; and iii) develop approaches to model the dependence of K_d values on groundwater chemistry, specifically ionic strength. In parallel, new sorption data from the literature that are most relevant to conditions of the candidate siting areas will be incorporated into NWMO's database.

9.4.5 Surface Area and Cation Exchange Capacity

Evaluations of solute transport and, in particular, characterization of sorption properties (e.g. sorption modelling, scaling of sorption) in safety assessment calculations, require estimates of external surface area (ESA) and cation exchange capacity (CEC) of the rock formations and infilling minerals.

The Brunauer, Emmett and Teller (BET) method (Brunauer et al., 1938) is used to determine the surface areas of samples as a function of total porosity and total sheet silicate (clay) content. This method was applied to sedimentary rocks from southern Ontario during detailed site characterization activities as part of OPGs Low and Intermediate Level Waste Repository proposal (INTERA 2011). Since that time, further research has been conducted at the University of Bern, Switzerland, on both sedimentary and crystalline rock samples to refine experiment protocols for measurement of BET at different grain sizes and for CEC. Two different CEC methods were investigated: i) triethylenetetramine copper(II) (CuTiren; Ammann et al. 2005; Meier and Kahr 1999); and ii) hexaamminecobalt (III) (Rémy and Orsini 1976). For both crystalline and sedimentary rocks, CuTiren results are considered to give the best approximations for the CEC of the rock. In the immediate future, these refined protocols will be applied as part of the characterization activities currently underway at specific sites. No further research and development is required at this stage, however, NWMO will continue to monitor the literature for developments in measurements of both ESA and CEC on relevant rock materials.

9.5 Geomechanical and Thermal Properties

Deep geological disposal induces short- and long-term effects in the rock mass, at both near- and far-field scales. The near-field effects include processes which occur in the host rock during the construction phase and which relate to the stability of underground openings: development of the excavation damage zone (EDZ), and the impact of de-saturation and stress release on long-term strength and deformation response of the host rock. During operation and post-closure, the temperature front generated by the used fuel advances into the geosphere, inducing changes in porewater pressure and/or flow. The latter will include areas beyond the excavation zone and into the host rock surrounding the repository. All of these phenomena are influenced by the in-situ stress regime at the repository site. Therefore, a thorough understanding of Thermal-Hydraulic-Mechanical (THM) processes is required for the design, construction, operation and safety assessments of a repository (e.g. ITASCA 2019; see also section 10.4.3).

9.5.1 In-Situ Stress

The in-situ stress state is a fundamental parameter for rock mechanics analysis and rock engineering design of a repository and the associated sub-surface openings. Both in-situ stress orientations and magnitudes play a crucial role in the response of underground openings to construction, as well as in the response of the repository and surrounding geosphere to short- and long-term processes. It is therefore very important to acquire reliable estimates of in-situ stresses at a repository site. However, this is impeded by the technical difficulties associated with obtaining reliable in-situ stress measurements, and consequently, the relatively small number of stress measurements which can practically be made at a site. The inherent variability in the in-situ stress state at a site due to geological complexities further complicates the estimates (Hakala et al. 2019). The in-situ stress state depends on a number of factors such as rock mass characteristics (i.e., heterogeneities, fabric, discontinuities, geological structure, faults, etc.) and the site loading history (e.g., tectonic activity, erosion and/or glaciation).

NWMO has compiled in-situ stress measurements in the Canadian Shield in crystalline rock and in southern Ontario (sedimentary rock). For the Shield region, Yong and Maloney (2015) updated the compilation and analysis of the in-situ stress database which was initially conducted by Kaiser and Maloney (2005). Consistent with past studies, best-fit relationships for three stress depth domains were identified: Domain 1 (stress-relaxed zone) from 0 to 300 m; Domain 2 (transitional zone) from 300 to 600 m; and Domain 3 (undisturbed zone) from 600 to 1500 m (Yong and Maloney 2015). A similar in-situ stress compilation study was completed for southern Ontario using the stress measurements from hydrofracturing and overcoring and their orientations along with the orientations of reported pop-ups, quarry floor buckles, and borehole breakouts in the region (NWMO and AECOM Canada Ltd. 2011). NWMO will continue to periodically update the stress database applicable to the selected site.

Currently available techniques to measure in-situ stress magnitudes and orientations include overcoring, the In-Situ Measurement Tool, conventional hydraulic fracturing and hydraulic testing of pre-existing fractures (e.g., Ask 2006; Lindfors and Perman 2007; Ljunggren et al. 2003; Sjoberg 2003). One or more of these methods may be applied as part of site characterization activities; currently it is envisioned that in-situ stress measurements will be made during sinking of the shaft. In the meantime, NWMO continues to monitor published literature for new in-situ stress measurements in Ontario, advances in in-situ stress measurement techniques and interpretation methods, as well as complementary estimation of in-situ stresses from borehole break outs, underground openings, and mine-by experiments.

In particular, stress variability in the case of limited, localized, and variable stress measurement data from a particular site is of particular interest. Jointly with SKB, NWMO is initiating a research project at the University of Toronto to investigate the role of statistical quantification of in-situ stress variability. Bayesian data analysis, in contrast to the customary frequentist analysis approach, applied to a multivariate model of in-situ stress can potentially overcome the stress variability problems in small datasets, and generate a multivariate stress tensor for use in rock engineering design. Through this new research project a hierarchical Bayesian multivariate model will be developed to refine stress regimes at a target site selected for inclusion in the research program. A protocol to apply the model to other sites (e.g. as part of site-specific studies) will also be developed.

NWMO will continue to monitor developments in techniques and approaches to measure and interpret in-situ stress conditions and to support new developments as opportunity arises. It is anticipated that these techniques and approaches will be applied during the characterization and construction phases and that NWMO will continue to maintain expertise through to the operations phase.

9.5.2 Rock Properties from Laboratory Experiments

The basic geomechanical properties of rocks are normally examined in laboratory-scale experiments using established methods. Historically, the Lac du Bonnet granite from the Whiteshell underground research laboratory in Pinawa, Manitoba was extensively studied (e.g. Davidson et al. 1994). Subsequently, NWMO has supported research on the geomechanical properties of low-porosity Ontario Cobourg limestone and, for comparison, the Jurassic limestone from Switzerland (Perras et al. 2018). A broad range of geomechanical properties including THM, poroelastic properties, and time-dependent strength and deformation were studied, as described in the following sections.

From a safety case perspective, the main question is the confidence in scaling from lab experiments to the in-situ conditions around a repository. This has been, and is being, addressed through developing improved tests and numerical models. The current work is aimed at a comprehensive understanding of the behavior of Cobourg limestone and the Lac du Bonnet granite (as an analogue for a crystalline host rock), and on the development of methods to understand the in-situ properties that can be applied to actual host rocks. The very low porosities of the potential host rocks (generally less than ~1% for a typical crystalline rock from the Canadian Shield, and between 1 and 4% for the Cobourg limestone), poses specific challenges for geomechanical characterization, which are addressed through the development of new laboratory techniques and tools through the research program.

The current laboratory-based research areas are summarized below. Given the importance of the geosphere as a structural barrier, it is anticipated that laboratory experiments on improving understanding of rock properties will continue, and will also include underground tests as part of geoscientific verification activities within the UDF at the site once construction begins.

<u>Effect of Scale on Mechanical Properties</u>

A major factor in determining properties a sedimentary rock such as the Cobourg limestone is selection of sample dimensions which capture a Representative Volume Element (RVE) of the rock. Density and unconfined compressive strength (UCS) measurements of cuboidal samples 50 to 350 mm in dimension were conducted, and it was concluded that the RVE of the Cobourg requires sample dimensions in the range of 100 to 200 mm (Selvadurai 2017). These dimensions are larger than conventional rock mechanics samples (normally 50 mm in diameter). Consequently, NWMO sponsored a research program at McGill University to develop a large-sample triaxial testing facility (Figure 9-3) that can test samples measuring 150 mm in diameter and 300 mm in length (Selvadurai 2017).

Research currently underway at McGill University will use the large-sample triaxial equipment to characterize the Lac du Bonnet granite and to examine potential scale effects on its geomechanical properties.

<u>Effect of Saturation on Mechanical Properties</u>

Within a repository, the rock will have different saturation ratios, as well as water contents in different locations, and at different times. In the vicinity of emplacement rooms, the host rock will become partially desaturated as a result of construction activities, whereas, farther into the rock mass, the rock will be in a fully saturated condition.

In order to quantify the effect of saturation on the strength of the Cobourg limestone, studies were conducted on 50 to 150 mm diameter samples, which were resaturated by different means. This research demonstrated that increases in water content achieved through resaturation efforts resulted in some reduction in UCS, CI, CD, and tensile strength of the rock relative to unsaturated rock (Jaczkowski et al. 2017).

Over the next few years, the effect of saturation on the mechanical properties of Lac du Bonnet granite will be studied, as an analogue for rock from a crystalline site.

Effect of Temperature and Stress on Mechanical Properties

In an earlier phase of the research at the University of Toronto, the effect of saturation conditions (dry versus saturated samples) and temperatures on the mechanical properties and permeability of Cobourg limestone were investigated (Nasseri and Young 2014). The experiments included preheating of samples at temperatures up to 100℃, and testing for UCS and triaxial compression at temperatures up to 150℃ under different confining stresses of 0-12.5 MPa and pore pressures of 0-5 MPa. UCS, stress-strain, static elastic properties, dynamic elastic properties (from P- and S-wave velocities), thermal expansion, and gas permeability were studied.

Through a preliminary thermal testing program at Queen's University (Pitts 2017) and ongoing research on thermal properties at McGill University, as well as a new research program at the University of Alberta, a full suite of thermal properties (i.e., thermal conductivity, thermal diffusivity, specific heat, thermal expansion coefficient) for both the Cobourg limestone and the Lac du Bonnet granite will be developed.

Ongoing research at McGill University is expected to study the effect of sample size, confining stress and temperature on THM properties of the Cobourg limestone and Lac du Bonnet granite. Included in the research objectives for the near term are investigations of the effect of stress on thermal conductivity of the Cobourg limestone and the Lac du Bonnet granite and exploring correlations between select thermal properties and mineralogical compositions of the rock (i.e., multi-phasic approach).

The new research program at the University of Alberta will complement the McGill program by investigating the mechanisms involved in re-saturation of low-porosity rocks such as the Cobourg limestone and Lac du Bonnet granite, quantifying the re-saturated state, and then studying THM properties of the rocks (e.g., strength, elastic properties, failure envelope, poroelastic properties, etc.) under high-temperature (potentially up to 125℃) in triaxial stress conditions.

Consequently, over the next few years, NWMO will acquire complete sets of THM parameters of the Cobourg limestone and the Lac du Bonnet granite necessary for coupled numerical modelling. This comprehensive understanding of these model rocks, and these methods, will be extended to the host rocks of the site characterization program.

Long-term Strength and Deformation

Historically, the long-term strength of the Lac du Bonnet granite was studied (Lau 2001; Lajtai and Bielus 1986; Lajtai and Schmidtke 1986). The results showed that increasing the confining stress from zero to 5 MPa increased the time-to-failure, while increasing the temperature from 50 to 75^{o}C reduced the time-to-failure.

NWMO recently sponsored a study involving static fatigue (constant stress) and relaxation (constant axial strain) behaviour of the Cobourg and Jurassic limestones. This work extended time-dependent testing to periods up to one year (Perras et al. 2018). Overall, the trend observed for time-to-failure versus driving stress from this research program was similar to that observed for the Lac du Bonnet granite by Lajtai and Schmidtke (1986). However, both limestones exhibited longer times to failure than the granite.

Creep and relaxation tests conducted under unconfined conditions provide conservative estimates of the long-term behaviour of the rock. In general, research studies on creep and relaxation tests under confining stress and elevated temperature are scarce. To better understand their effects on long-term rock strength, NWMO will explore the possibility of conducting long-term strength and deformation tests of rock under confining stresses equivalent to the swelling pressure of the bentonite within the engineered barrier system, and/or at the elevated temperature(s) relevant to a repository.

Poroelastic Properties

Various poroelastic properties (Biot coefficients, Biot modulus, and Skempton's pore pressure coefficient B) are among the parameters required for coupled THM modelling of a repository. These are difficult to measure due to the low porosity of the potential host rocks. Selvadurai (2018) developed a semi-analytical method to determine the Biot coefficient for the Cobourg limestone. Specifically, the compressibility of the solid phase was estimated based on the theory of multi-phasic elastic solids.

Research currently underway at McGill University will determine the poroelasticity parameters of the Lac du Bonnet granite (samples up to 150 mm in diameter) using both conventional experimental techniques and indirect analytical methods (e.g., multi-phasic approach). The results will be compared with values available for other granitic rocks from Finland, Sweden, and Switzerland.

Rock Joint Properties

The overall mechanical response of the rock around the repository will also be influenced by the presence of natural discontinuities and those induced during repository construction and operation. Characterization of rock discontinuities, joint surface roughness, and effect of stress on joint stiffness in both Constant Normal Load (CNL) and Constant Normal Stiffness (CNS) conditions are currently underway at Queen's University. This program will complement the fracture characterization studies though the POST project described in Section 9.5.3.

Brittle Failure Modelling

Crack Initiation (CI) and Crack Damage (CD) stresses are important input parameters for studying brittle failure of rock around underground openings (i.e. Excavation Damaged Zone or

EDZ). Through a compilation and analyses of laboratory data from the Forsmark granite, various interpretation methods for estimation of CI and CD were revisited (Diederichs et al., 2014). Select methods were then also applied to new test results from the Cobourg limestone conducted as part of the research program (Jaczkowski et al. 2017).

Preliminary EDZ modelling work (Section 10.4.1.1) revealed that, for improved predictions of EDZ, it is important to consider the post-yield evolution of material parameters including i) the rate of strength loss, and ii) the dilation parameter which controls volumetric expansion of the damaged rock. Therefore, triaxial test data on three sedimentary rocks (Indiana limestone, Carrara marble, Toral de Los Vados limestone) were compiled and re-analyzed to provide the necessary input parameters for brittle damage modeling of EDZ (Diederichs et al. 2014). Additionally, a new dilation model was proposed by Walton and Diederichs (2014) based on triaxial compression test data of a wide variety of rocks (sedimentary rocks, diabase, marble, granites, and quartzite).

<u>Estimating Rock Mass Strength</u>

The common Hoek-Brown criterion is primarily used deterministically to estimate rock mass strength and stiffness parameters from laboratory test data. To quantify the uncertainty in laboratory data, statistical methods were applied to measurement results from intact samples to assess the correlation between different Hoek-Brown model parameters, and used to calculate a mean intact strength envelope with improved accuracy (Diederichs et al. 2019; Langford and Diederich 2015).

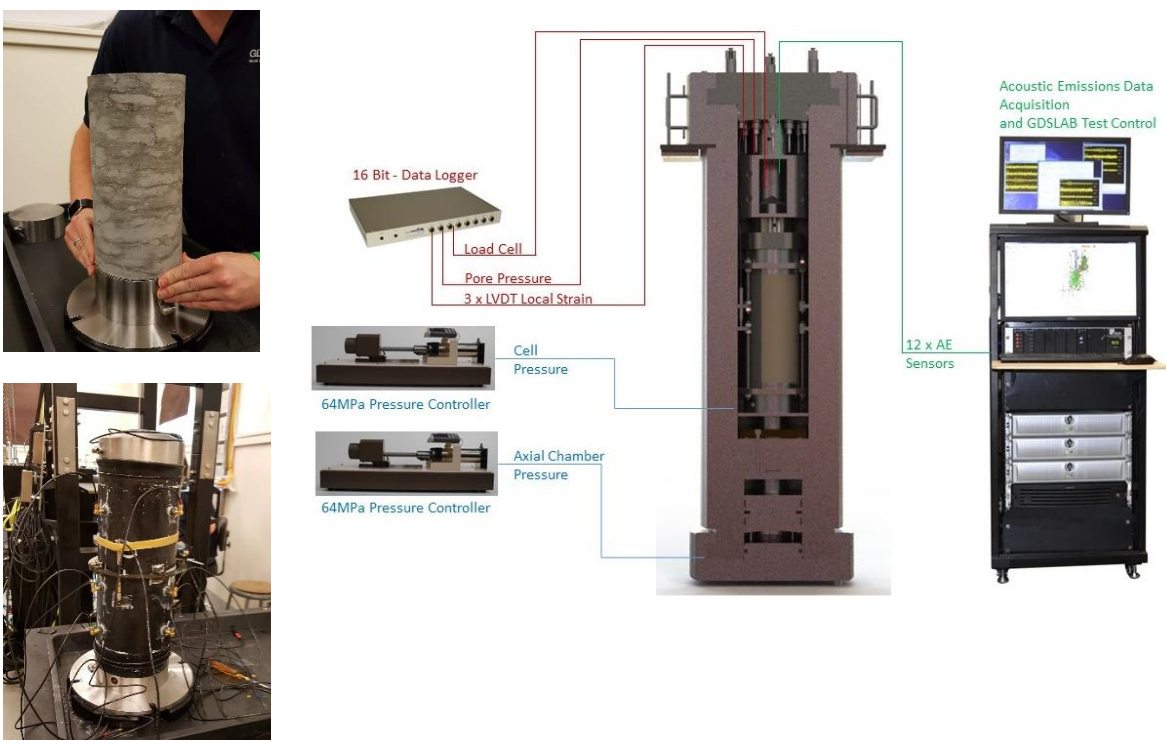

Figure 9-3: Large-sample Triaxial Testing Facility at McGill University

Development of New Measurement Methods

While photogrammetry techniques provide surface deformation data over large areas, and conventional extensometers give discrete measurements on internal strains, distributed fiber optic sensors can detect continuous small-strain data through the different stages of rock failure within the EDZ zones. NWMO recently conducted a state of knowledge review of fiber optic sensors for measuring strain distribution along ground support members used in underground openings (Diederichs et al. 2019). In subsequent tests at Queen's University, Distributed Optical Strain (DOS) sensors were used in pullout testing of several ground support members: rebar, grouted cable bolt, grouted coaxial bolt, and double shear plane testing of a grouted rebar. The encouraging results from these tests suggest that the optical sensing technique can provide significant benefit to improve the mechanistic understanding of support response (Diederichs et al. 2019; Forbes et al. 2016). The application of fiber optic sensors is being expanded to include strain sensing in laboratory testing of rock samples (uniaxial compression, triaxial compression, and direct shear testing under both CNL and CNS conditions), as well as in-situ measurements. Local strain measurements using strain gauges will be used for calibration of fiber optic strain sensing. Effectiveness of various configurations of the sensors will also be examined.

Sampling for geomechanical testing (e.g. UCS, triaxial) is a discrete process. The resulting data collected from testing samples at defined intervals, while likely sufficient to quantify mean values for formations and units within the strata, may not fully capture the inherent variability in particular, in sedimentary rock. Queen's University is currently investigating laboratory acoustic velocity logging against continuous core logging.

The NWMO continues to monitor new developments in measurement methods, in particular through participation in international joint projects, which provide an opportunity to gain experience in current measurement methods. This is noted in the following section.

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

In addition to work based on improving laboratory measurements of rock properties, NWMO participates in projects that provide in-situ or large-scale experiment data. Key past Canadian projects are the AECL Mine-By Test and the Heated Failure Test at the Whiteshell URL. NWMO is currently involved in geomechanical studies as part of the POST fracture parameterization project, and at the Mont Terri Project.

POST Project

In 2014, SKB, Posiva and NWMO initiated a joint research program to provide guidelines for determining the parameters necessary for assessing fracture stability at the deposition tunnel scale (POST). Initially, the concept was to conduct an in-situ test at the Äspö URL, by isolating and shearing an existing fracture. However preliminary laboratory shear tests were conducted on rock cores containing a gently dipping fracture. The results demonstrated that the required boundary conditions, which would be more representative of a confined fracture deep underground, could not be achieved. In addition, preliminary numerical simulations predicted that displacement along the target fracture would not be detectable in-situ. It was concluded that fracture parameterization and upscaling would be done through numerical simulations . To obtain data on large-scale fractures for use in numerical modelling, a large shear box (Figure 9-4) which can accommodate samples up to 500 mm long and shear displacements of up to 50 mm under constant normal load (CNL) and high CNS values is currently being constructed. Going forward, the experimental results of various size samples from a quarry near Forsmark, Sweden will be used to develop and verify discrete element modelling to obtain a constitutive relation to estimate fracture strength. Once developed, this constitutive relation could be applied as part of site-specific studies conducted in the UDF.

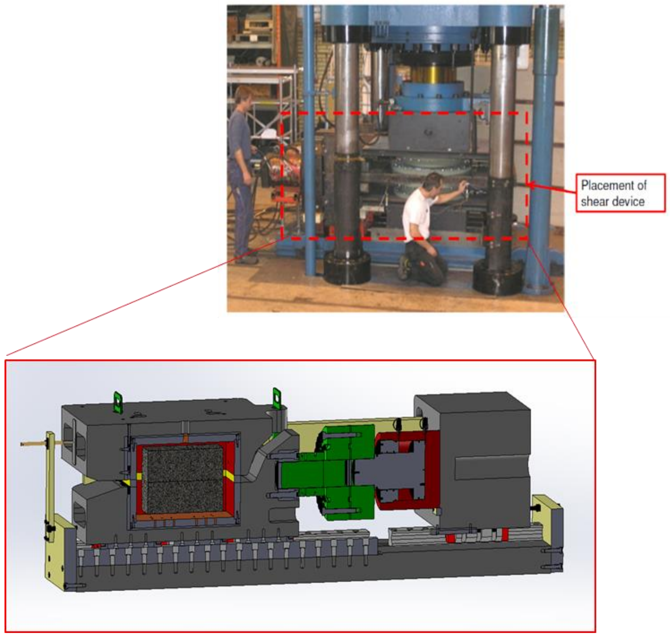

Figure 9-4: Large shear box equipment capable of testing samples 500 mm long containing fractures under high constant normal stiffness

Mont Terri Project

NWMO continues to participate in two geomechanical experiments (FE-M and GC-A) as a partner in the international Mont Terri Project in Switzerland.

The long-term Full-scale Emplacement Experiment (FE-M) includes a full-scale heater test in the Opalinus Clay. The experiment includes investigation of repository-induced THM coupled effects (e.g., temperature, saturation, pore pressure, stress, and deformation) on the backfill and the host rock.

The GC-A experiment is focused on characterization of EDZ development within the Opalinus clay. In addition, in-situ stress state will be measured using several methods, including a dilatometer probe, and a new pressuremeter tool developed by the University of Alberta which is called the Reservoir Geomechanics Pressuremeter or RGP. EDZ development will be characterized using several techniques in-situ, including: geophysical method (i.e., close-range hyperspectral imaging) during excavation from shaly to sandy facies; 3D convergence measurements of the niche; and tracing resin-injected area by drilling radial boreholes. Involvement in the back-analysis of the GC-A data will enhance our understanding of EDZ development in heterogeneous sedimentary setting.

Future work

NWMO will apply the experience and methodologies developed through participation in these international joint projects to future in-situ experiments to be conducted as part of geoscientific verification activities within the UDF at a selected site.

9.5.4 Numerical Modelling of Geomechanics

Repository design and safety assessment apply the understanding of rock behaviour determined using the laboratory and field work described earlier through the development of numerical simulation tools to understand the behaviour of the repository rock mass and predict excavation damage processes.

The requirements to forecast the long-term response of the rock mass containing a repository exceed traditional design expectations for underground civil or mining projects. For this reason, the research program continues to advance the state of scientific knowledge and engineering regarding EDZ mechanics as well as changes related to temperature front advancement (e.g. porewater pressure and flow, deformation in the vicinity of the openings and into the rock mass). Rock behaviour is examined at the grain scale through the laboratory scale to full repository scale. The program also addresses a range of time scales from static conditions through variable stress paths and loading rates in low porosity sedimentary and crystalline rocks, the two primary geological environments being considered for a used nuclear fuel DGR in Canada.

For numerical simulations, commercial geomechanical codes are available and used in the NWMO program, including for example FLAC3D (Radakovic-Guzina et al. 2015). Two methods that have been developed and undergone testing by NWMO are the Synthetic Rock Mass and Rock Mass Effective properties approach, as described below.

Synthetic Rock Mass (SRM) Project

The Synthetic Rock Mass (SRM) was a multi-year research project funded by NWMO and SKB. This program brought together researchers from Queen's University and the University of Alberta and SKB to understand the failure mechanisms of a rock mass containing a DFN. Utilizing discrete element logic, the SRM approach can capture the fracturing of intact rock and the movement along an existing DFN. This approach enables rock mass behaviour to be understood at multiple scales including grain and sample scales, and the extent of EDZ in underground excavations to be assessed.

Through this research, SRM models were developed at different scales to understand the influence of stress path (Duran del Valle 2017), initial confinement (e.g., Vazaios 2018), and relaxation on damage evolution. Grain scale models were capable of closely matching laboratory test results (Ghazvinian 2015). Upscaled models showed encouraging results when compared against EDZ in underground excavations (Farahmand 2017).

NWMO will continue to monitor the literature and may support further research on SRM methodologies in the future, as opportunities or needs arise.

Rock Mass Effective Properties

SRM modelling approaches allow for an explicit representation of DFNs in the rock mass and numerical estimation of mechanical and hydraulic properties of the rock. The SRM approach, however, is far from sufficient to define effective properties of rock mass at repository relevant DFN scales. Consequently, an appropriate approach for determination of rock mass effective properties could include a hybrid of analytical developments (e.g. Darcel et al. 2015; Kachanov 1993) and SRM modelling.

Since 2016, NWMO has been supporting SKB to: (1) design a methodology and a software tool to predict the evolution of rock mass effective properties with scale using a multi-scale DFN approach, including elastic properties and permeability; and (2) apply the methodology to rock mass models in various settings, including an effective/explicit representation of fractures into modelling applications.

Going forward, NWMO will continue to develop expertise and methodologies which in the future, can be applied to site specific data collected during the characterization and construction phases (i.e., as part of geoscientific verification activities within the UDF).

9.6 Research Program Summary

For many of the geosphere properties which must be characterized at a proposed repository site, methods are well-established and several are already being (or will be) applied as part of preliminary assessments in both crystalline and sedimentary rocks. For these properties, additional research is not needed, although NWMO continues to actively monitor developments in specific areas of interest, as discussed above. Other areas of active research, such as the development of numerical methods to generate geostatistically representative fracture networks, will continue in parallel with the site investigations program, for application during detailed site characterization activities. Subsequent research and development will focus on methods or approaches which can be applied once construction of the underground facilities begin, as part of geoscientific verification activities.

Site Selection and Characterization Phase

New or refined laboratory-based methods, numerical approaches and expertise developed for the characterization of very low porosity, low permeability rocks are currently being applied as part of site investigation activities, or will be applied as part of detailed site characterization activities at the selected site. Development of new and/or improved methods for characterization of rock properties at different scales (laboratory, in-situ) and for upscaling in terms of both space and time will continue throughout this phase.

Methods for scaling up from core-scale to larger scale laboratory methods, and for in-situ measurement of rock properties is being developed, in part through involvement in international joint projects at underground research laboratories.

Site Preparation and Construction Phase

During this phase, the site investigation will shift to geoscientific verification activities within the repository, and in particular in the UDF, and will include the following:

- Measurement of rock properties within the repository to verify results from prior surface based studies.
- EDZ characterization.
- Initiation of long-term, in-situ tests:
    - Geochemical: collection of porewater from seepage boreholes, microbial experiments
    - Geomechanics: temperature advancement, pore pressure, stress and displacement measurements in the host rock

Both methods and expertise acquired through the research program will support these verification activities. It is envisioned that long-term diffusion experiments within the UDF would be conducted through the technical research program.

Operations and Extended Monitoring Phase

The in-situ tests will continue to be monitored until the time when instruments need to be removed in order to facilitate repository decommissioning and closure. Additional long-term experiments may be developed within the UDF to further verify or reduce uncertainities in particular geosphere properties, if required.

Major Facilities

No major facilities are required prior to construction. It is envisioned that in the near-term, research programs described above will continue to be conducted in University environments or through international collaborations in underground research projects. The primary facility required during construction is the UDF.

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10 LONG TERM GEOSPHERE STABILITY

As described in Section 9, the geoscience program for a candidate site will be designed to support the safety case, including development of a site model (Descriptive Geosphere Site Model - DGSM) based on the geosphere properties and characteristics determined during site characterization. This chapter describes research conducted to further understand the processes affecting the stability of the repository and the surrounding geosphere, as required to demonstrate the safety of the repository over the long-term. The processes and factors considered are:

- Long-term climate change - glaciation – includes assessments of crustal rebound stresses, erosion, and permafrost;
- Groundwater stability – flow, transport, geochemical and redox stability;
- Seismicity;
- Geomechanical stability; and
- Other geoscientific studies to support geosynthesis for a particular site – e.g. assessment of natural resource potential.

The approaches, methods and scientific understanding advanced through these research programs will support the development of the DGSM and Geosynthesis, with the objective of describing geosphere behaviour at various spatial scales (e.g. site, sub-regional and/or regional) for time periods up to 1 Ma. Processes which are not expected to impact repository evolution within the 1 Ma timeframe over which safety must be demonstrated, such as volcanic activity, are not considered within the research program. Potential impacts of climate change on biosphere evolution are discussed in Section 11.5.

The initial application of approaches, methods or results from the research program in preliminary assessments as part of the current site selection phase, or in preliminary safety assessments or engineering designs are also briefly described. Research to advance process understanding and to maintain scientific expertise on long-term geosphere stability is expected to continue through to the decommissioning phase.

10.1 Long-term Climate Change - Glaciation

Glaciation associated with long-term climate change is considered the strongest external perturbation to the geosphere at repository depths. Potential impacts of glacial cycles on a deep geological repository include increased stress at repository depth caused by glacial loading, penetration of permafrost to repository depth, recharge of oxygenated glacial meltwater to repository depth, and the generation of seismic events and reactivation of faults induced by glacial advance (depression) or by rebound following ice-sheet retreat.

Although the current and increasing inventory of anthropogenic gases in the atmosphere may delay the onset of the next glacial cycle, the possibility of future glaciations during the 1Ma period for which safety of a repository must be demonstrated cannot be excluded (Peltier, 2011). Assuming that the Canadian landscape could be subjected in the future to glaciation events similar to those that have occurred over the past million years of Earth history, a physical model which has been constrained to the most recent events in the Late Quaternary period of Earth history is used, in turn, to constrain the potential impacts of glaciation on the subsurface environment. This physical model is the University of Toronto Glacial Systems Model (UofT GSM) as described in Section 10.1.1 below, and is used to provide a geoscientific basis to understand ice sheet dynamics, ground surface temperature, isostatic depression and permafrost evolution as it would occur at a repository site in the future.

The main areas of research associated with glaciation are focused on further refining scientific understanding of the potential impacts associated with the advance and retreat of ice sheets, as described in the following subsections.

10.1.1 Surface Boundary Conditions

To determine the potential impact of glaciation on the safety and stability of a DGR site, an approach to determine geologically plausible surface boundary conditions during glaciation is required. In NWMO's studies, the boundary conditions which could be expected during future glacial events are defined based on results from the UofT GSM. The UofT GSM is a state-of-the-art model which has been recently validated with respect to the existing Greenland and Antarctic ice-sheets (Stuhne and Peltier 2015a).

In NWMO's work, the UofT GSM is used to generate a set of realizations to describe the advance and retreat of the last ice-sheet over the North American continent during the last glacial cycle which occurred in Canada between 121,000 years ago and the present (Peltier 2002, 2003, 2004, 2006a, 2006b; Stuhne and Peltier 2015b, 2016, 2017). The analyses performed using this model recognize that it is impossible to provide a unique description of the detailed characteristics of such an event. The approach adopted is based upon the use of a range of ice-sheet realizations that are compatible with the geological constraints that can be brought to bear upon the characteristics of the most recent North American glaciation event of the Late Quaternary ice-age. It is expected that the range of plausible ice-sheet realizations derived on the basis of this methodology is sufficiently broad to encompass the conditions that would likely be expected in the general region of a repository site.

The realizations generated by the GSM provide varying magnitudes and rates of change in basal normal stress, past ice thickness, permafrost thickness, basal temperature, meltwater production, lake depth, and other two-dimensional, time-varying fields. This information is then used as the local boundary conditions for numerical modelling to illustrate the long-term evolution of the deep groundwater system (Section 10.2), the repository (section 10.4), and to provide an estimate of the maximum ice sheet thickness to support engineering design.

Additional modelling capabilities to UofT GSM are currently been developed to deliver improvements to simulations of Laurentide ice sheet evolution, as described below.

<u>Impact of Glaciation on the Great lakes</u>

As the Laurentide ice-sheet retreated, the generation of glacial meltwater resulted in changes to the surface hydrology. The characterization of the glacial meltwater in the UofT GSM, and the impact of glacial meltwater on the formation of proglacial lakes, as well as the evolution of the Great Lakes is being investigated.

<u>Erosion</u>

The extent of erosion during glacial advances and retreats is being investigated, including the potential impacts of ice-streams on estimates of erosion rates, as well as an overview of glacial erosion during the Laurentide ice-sheet.

Onset of Future Glaciation Events

In previous studies, the advance and retreat of the Laurentide ice-sheet has been used to determine the impact the glaciation on a deep geological repository site. This research investigates the onset of the next glacial episode and the arrival of an ice sheet at potential repository locations under conditions similar to those during past glaciations, as well as under conditions impacted by current anthropogenic impacts on climate.

To support future geosynthesis activities, UofT GSM will be used to develop a range of plausible realizations (or re-creations) of ice sheets in the general region where siting of a repository is being considered. The boundary conditions determined using these realizations will then be used in assessments of groundwater system stability and repository stability, in support of a safety case. It is expected that NWMO will continue to maintain activities in glacial modelling, and periodically update its estimates in support of licencing applications.

10.1.2 Crustal Rebound Stresses

The horizontal rebound stresses due to glacially induced lithospheric flexure and relaxation of the mantle are required input for long-term, geomechanical assessments of shaft and cavern stability (Section 10.4.3). The rebound stress components, when superimposed on the more permanent lithostatic and tectonic stresses, constitute the total stress of the in-situ stress regime of a deep geological repository (e.g. Wu 2012).

To estimate the rebound stress components due to future glacial rebound, numerical computations were completed using 12 combinations of earth models and ice models from the ICE-6G ice model (Peltier et al. 2015) over all of Canada as a function of time (over the past 120 ka and a full glacial cycle). The computations were completed using the Finite Element method described in Wu (2004). Rebound stress tensors were computed, including normal stresses and shear stresses at 850 m depth for a 1x1 degree grid covering the Ontario portion of Eastern Canada.

There are two earth model parameters that are not well determined but will affect the magnitude of the calculated flexural stress – lithospheric thickness and mantle viscosity. A thicker lithosphere results in less flexure (wavelength) and less flexural stress. A lower mantle viscosity results in a faster rate of rebound. For deformations with time scales of the order of thousands of years, the average thickness of a laterally homogeneous continental lithosphere is assumed to be around 125 km (Model L125).

Two additional models were also considered. For assessing the maximum flexural stress, a model (L075), which is only 75 km thick was used. To capture that, in reality, lithospheric thickness varies laterally, the model LAT of Wang & Wu (2006) was used. The latter was deduced from seismic tomography and has thickness of 180 km under and west of Hudson Bay (near the center of the North American craton) and decreases to about 50 km over the oceanic area. In the LAT model, variations in lithosphere thickness are represented by 5 layers which vary in thickness laterally.

The maximum horizontal stress from all the models considered is compressive, with a magnitude slightly less than 20 MPa. The maximum vertical stress is also compressive with a magnitude of 25.3 MPa, which was produced from a model with a thin, 75 km lithospheric thickness and 3×10^{21} Pa s lower mantle viscosity. This work is state-of-science and considered sufficient unless there is significant revision in our understanding of lithosphere thickness, thickness variability and mantle viscosity. If substantial refinements are made to the mantle viscosity used in the UofT GSM, an update to the rebound stress components may be required. We will therefore continue to monitor the literature and explore this topic through the UofT GSM model (Section 10.1.1) and its linkage to mantle viscosity.

10.1.3 Long-term Erosion

Long-term geomorphic processes are controlled by nonlinear episodic erosive events such as tectonic processes and glaciation, and by lithology and climate. It is difficult to quantify the long-term (10^3 to 10^6 years) rate of erosion attributable to episodic processes, even if they exceed steady rates (Margreth et al. 2016). In particular, the quantification of low erosion rates on plateaus is important, because low-relief, high-elevation surfaces are often used as reference points for estimates of total glacial erosion in adjacent valleys, assuming that the plateaus remained nearly unaltered throughout the Quaternary (Small and Anderson 1998).

In the context of demonstrating the safety of a DGR, the primary process expected to result in erosion over the next million years is glacial activity. A number of studies have produced estimates of the amount of erosion by the Laurentide Ice Sheet and Fennoscandian ice sheets. Bell and Laine (1985) originally estimated total erosion on a continental scale of 120 m over the last 2-3 Ma. However, most subsequent work suggests that total erosion during the Quaternary did not exceed 10 m to 40 m for both the Laurentide Ice Sheet and Fennoscandian ice sheets (e.g. Hay et al. 1989; Lidmar-Bergstrom 1997; Melanson et al. 2013; Ebert, 2015). A state-of-science review of erosion in crystalline environments of the Canadian Shield, similar to that conducted by Hallet (2011) for the sedimentary rocks of southern Ontario, will begin in 2019. This review will focus on glacial erosion rates and processes, including a survey of methodologies used to measure glacial erosion rates, with an emphasis on terrestrial cosmogenic nuclides, and a synthesis of factors that control glacial erosion and a ranking of their relative importance in a geological and glaciological setting similar to crystalline bedrock in Ontario. This review, in turn, will provide support for geosynthesis activities for a specific site in crystalline rock.

Hallet (2011) reviewed several independent types of geological evidence in order to assess the magnitude of total erosion which would likely occur over one glacial cycle in the sedimentary rocks in southern Ontario at different scales, from regional to local. In this assessment, it was assumed that the siting region will be subjected to major glacial cycles, recurring every ~100,000 years, much has they have over the last ~900,000 years. Geological data and reconstructions of the Laurentide ice-sheet during the last major glaciation from Peltier (2011) were used to assess the amount of erosion expected over the next glacial cycle. Thirteen estimates were presented which support the conclusion that bedrock erosion would not exceed many tens of meters in southern Ontario over one glacial cycle; no erosion and net deposition of sediments in the region is also possible.

Through the research program, the NWMO will stay abreast of the current scientific literature pertaining to glacial erosion in both crystalline and sedimentary rocks, and to be involved in international projects as opportunities arise.

As part of site characterization activities in both crystalline and sedimentary environments, field investigations will be conducted of topographic features, or other known factors that might tend to localize erosion at a potential site. These will be described in the site characterization plan.

10.1.4 Glacial and Proglacial Environment (Ice Sheets, Permafrost, Taliks)

When ice is present over a repository site, the conditions at the base of the glacier or ice sheet form a surficial boundary condition to the underlying groundwater system (Section 10.1.1). Depending on whether the conditions at the glacier bed are melted or frozen determines whether free water is available to recharge the groundwater system. The physical bed conditions determine whether the glacier basal drainage system between ice and bedrock is fully connected to the groundwater system (as is the case where the glacier bed is composed of thick, saturated sediment), or if recharge to the groundwater system is limited to discrete drainage system elements developed across the surface of the bedrock. Further, drainage system processes at the ice-earth interface redistribute and focus water at the glacier bed, creating a water pressure field that is spatially and temporally variable. These and other glaciological factors therefore impact the mechanical and hydrogeological boundary between ice and earth domains, and potentially influence gradients that develop over the course of a glacial cycle.

A combination of field and numerical modelling studies are used to further scientific understanding of processes under an ice sheet, and within the proglacial environment in front of an ice sheet (e.g. extent and nature of permafrost). An important focus for these studies is potential implications on the stability of the groundwater system at repository depths.

Through to decommissioning, NWMO will continue to monitor the scientific literature for field, numerical or other studies relevant to understanding processes related to basal conditions of ice sheets and the proglacial environment.

10.1.4.1 Field & Laboratory Studies

In earlier stages of the research program, laboratory experiments were conducted to evaluate the potential impact of permafrost formation on the chemical and isotopic composition of groundwaters within the Canadian Shield (Zhang and Frape 2002). In 2001, Posiva, Nirex (UK), SKB, the Geological Survey of Finland and Ontario Power Generation initiated the PERMAFROST project to improve scientific understanding of the influence of climate evolution on groundwater systems in crystalline terrains. In the first three phases of this project, field research was conducted at the Lupin Mine in Nunavut, Canada, in an area of continuous permafrost that extends to a depth of 500 m (Frape et al. 2004b; Stotler et al. 2009). The objective of the fourth phase of the field research conducted at High Lake, Nunavut, was to obtain fluid samples from beneath a permafrost layer which had not be impacted by mining activities (Holden et al. 2009).

One of the few ways to investigate the ice sheet boundary condition relevant to future repository assessment is to study a modern-day analogue such as the Greenland Ice Sheet (GrIS). The most comprehensive effort to directly investigate hydrological processes related to the presence of an ice sheet to date was the Greenland Analogue Project (GAP) funded by SKB, Posiva, and NWMO (Claesson Liljedahl et al. 2016). This research examined the temporal and spatial nature of processes occurring on the ice sheet surface, conditions at the ice sheet bed (thermal and meltwater generation), and interactions between glacial meltwater and the underlying groundwater systems.

Several key findings from the GAP contribute to improved scientific understanding of processes associated with ice sheets and cold climate, including:

- At the surface of the ice sheet: Surface melt and runoff is a summer phenomenon limited to 3-4 months (May through September). Nearly all surface melt eventually penetrates the ice and reaches the bed. Just above the equilibrium line altitude (ELA), where meltwater begins to pool, is approximately the interior limit where substantial surface melt has the potential to penetrate to the bed. The volume of meltwater generated at the surface each summer was found to exceed the amount of predicted basal melt by two orders of magnitude (cm of basal melt vs. metres of surface melt).

- At the ice sheet bed: Direct observations made in 23 boreholes drilled to the ice sheet bed at distances between 200 m and 30 km from the ice margin provide the first direct evidence that the entire outer flank of the study area has a melted bed, with liquid water present, rather than a universally or locally frozen bed. Modelling of the boundary between melted and interior frozen conditions indicate that a central frozen area extends many tens of kilometres from Greenland's central ice flow divide, but greater than 75% of the studied sector of the GrIS is subject to basal melting conditions.

- Hydraulic boundary conditions for groundwater simulations: Between the ice divide and the margin, there is evidence for three different basal zones as defined by the amount and configuration of meltwater: the frozen bed zone (at the centre of the ice sheet), the wet bed zone, and the surface-drainage bed zone (closed to the ice sheet margin). This revised conceptual understanding of the drainage system implies that much of the bed inward of the margin is covered by water, rather than mostly drained by discrete conduits with little water in between. Taken together, hydraulic measurements and analyses from the ice boreholes imply that ice overburden hydraulic pressure (i.e. a hydraulic head corresponding to 92% of ice thickness) provides an appropriate description of the basal hydraulic pressure as an average value for the entire ice sheet over the course of each year.

- Role of permafrost and taliks: Close to the ice sheet margin, the permafrost thickness was observed to reach 350-400 m. Where permafrost extends to depths of greater than 300 m, a lake diameter of approximately 400 m would be expected to maintain unfrozen areas throughout the entire permafrost thickness, e.g. through taliks, which provide a potential pathway for exchange of deep groundwater and surface water. A borehole drilled underneath a lake confirmed, for the first time, the existence of a through talik beneath a lake in an area of continuous permafrost. Although it had been hypothesized that the lake would act entirely as a discharge feature, evidence from hydraulic head measurements and the stable water isotopic composition of the sampled groundwaters are consistent with seasonal recharging conditions occurring at this location.

Research to further understand boundary conditions at the base of ice sheets continued through the Greenland "ICE" project. Access to the full ice thickness was created through nine boreholes drilled to the bed, and monitored for three years. Findings are summarized in Harper et al. (2017, 2019); Wright et al. (2017); and Meierbachtol et al. (2016a, 2016b, 2018).

No further field activities are planned in the near term. Current research is focused on the further integration of data collected during the Greenland projects, as described in the following section.

10.1.4.2 Numerical Modelling

In 2019, NWMO and other organizations initiated a university-based, four-year research program (CatchNet) on modeling of permafrost environments. The research will be conducted through Ph.D. research programs and will focus on:

1. Subglacial and periglacial hydrogeological connections at the landscape scale, based on observational data from sites in Greenland.

2. Groundwater – surface water interactions over a range of permafrost conditions and transitions from no permafrost to permafrost conditions. Catchment-scale modeling will be linked to a range of sites in Sweden, Canada, and Greenland.

3. Biogeochemical cycling and evapotranspiration processes in permafrost environments.

Also in 2019, SKB and NWMO partnered to provide support for researchers to conduct numerical modelling of connections between glacial and sub-glacial hydrology and the periglacial hydrological system on landscape scale using observational data from the GAP. This research, which is complementary to the CatchNet program described above, will advance scientific questions related to the understanding of how the sub-glacial hydrological system connects to the hydrological system of the periglacial landscape today. In this way, the research will provide an improved basis for formulating relevant assumptions and evaluating conservativeness in safety assessment analyses.

10.2 Groundwater System Stability

A synthesis of structural geologic, hydrogeochemical and hydrogeological evidence gathered during site characterisation activities will be used to assess long-term groundwater system evolution and stability at a potential repository site. As part of the synthesis process, numerical methods that provide a systematic framework to integrate independent site-specific data sets will be applied (e.g. Sykes et al. 2004, 2009; Normani et al. 2007, 2014; Normani and Sykes 2014). These techniques provide insight into the present day groundwater system (Section 9.2.2), as well as the response of that system to external events such as glaciation which may occur in the future (next section). Numerical simulations can also be used to evaluate and constrain uncertainty with regard to geosphere performance.

Uncertainties in the future evolution of groundwater compositions are coupled to uncertainties about the movement of groundwater. Similarly, impacts of glaciation at repository depth will be dependent on site-specific conditions. The age of, and potential influence of glaciation on, groundwaters and porewaters cannot be determined directly; instead, they are inferred from paleohydrogeological evidence, such as stable water isotope ratios (Section 9.3.4), and fracture mineralogy (Section 9.1.6). Together with numerical tools, such as reactive transport modelling, this information can be used to illustrate the potential evolution of geochemical conditions at repository depths. In the following sections, on-going research on different integrative tools and approaches to assess the stability of groundwater systems are described.

10.2.1 Groundwater Flow and Transport

As mentioned previously, glaciation is expected to be the single greatest external perturbation to the groundwater system at depth over the next 1 Ma timeframe. The influence of glaciation on the groundwater systems is represented in groundwater models through the application of varying paleohydrogeologic surface boundary conditions, as described in Section 10.1.1.

In the event of glaciation, the interconnected network of fractures in crystalline rock will act as potential conduits, allowing glacially-derived meltwater to recharge into the system. Where present, dense brines within the geosphere can lessen energy gradients limiting recharge of low salinity, oxygenated glacial meltwater to repository depths. Numerical modelling of the potential effects of ice sheets on groundwater flow systems considering Hydraulic-Mechanical (HM) coupled behavior in three dimensions was conducted by Chan et al. (1998) using the code MOTIF. As part of the international DECOVALEX Project, Chan and Stanchell (2004) employed both 2D and 3D coupled hydraulic-mechanical simulations to investigate the response of a fractured crystalline rock mass at site-scale (tens of kilometres) to glaciation. The site-scale HM model was based primarily on site-specific data from the Whiteshell Research Area in the Canadian Shield, with simplifications and generalizations to accommodate Fennoscandian Shield information. The transient surface boundary conditions used in the HM model were generated by a continental scale model of the Laurentide ice sheet over the last glacial cycle (~100,000 years) developed at the University of Edinburgh. A later study by Chan et al. (2008), also conducted as part of the DECOVALEX project, explored different upscaling strategies from detailed, discrete representations of fractured rock, to equivalent continuum representations applicable at the repository scale. The impact of different upscaling strategies for the thermo-hydro-mechanical (THM) properties on predictions of relevance to repository far-field performance, and the extent to which THM-coupling needs to be considered in relation to safety assessment measures, were also examined. More recently, studies have been conducted to examine how the advance and retreat of an ice sheet affects the stress state of the Earth, and how those stress changes influence the stability of faults at two proposed repository sites in Sweden (Lund et al. 2009) and a repository site in Finland (Lund and Schmidt, 2011). Results from these studies demonstrated a strong dependence of fault stability on the glacially-induced excess pore pressure.

As part of the hydro-mechanical numerical analyses of groundwater flow with regional (~5700 km^2) and sub-regional (~100 km^2) watersheds conducted for crystalline rock by Normani et al. (2003; 2007), Sykes et al. (2003; 2004; 2009), Cornaton et al. (2008), Park et al. (2008) and described in Section 9.2.2, transient long-term boundary conditions were also investigated. The paleohydrogeological simulations investigated the role of varying paleoclimate boundary conditions and the characterization of hydromechanical coupling. Chan and Stanchell (2008) also conducted a numerical case study of THM processes and mechanisms arising from glaciation, for the subregional, fractured flow system adapted from Sykes et al. (2004). In all of these studies, the varying boundary conditions with time were provided by considering several different realizations of the last glacial cycle using the UofT GSM (Section 10.1.1). Detailed evaluations of the potential effects of glaciation on regional and site groundwater systems in crystalline environments are provided in Normani (2009), Walsh and Avis (2010), and Normani and Sykes (2014). Paleohydrogeological sensitivity cases were most recently demonstrated through application to a hypothetical site in crystalline rock as part of an APM postclosure safety assessment (NWMO 2017). The next application of these numerical modelling approaches will be to specific sites, as part of the preliminary assessments underway in crystalline rock environments.

Paleohydrogeological simulations of groundwater flow and transport in sedimentary rocks within the Michigan Basin, southern Ontario were conducted as part of OPG's proposed low and intermediate level waste (L&ILW) DGR project (e.g. Sykes et al. 2011). A quantitative assessment of the impact of glaciation events on a hypothetical repository in sedimentary rock was conducted by Avis and Calder (2015). The evolution of the groundwater flow regime in a 3D domain at the sub-regional scale (tens of kilometres) and local scale for eight glacial cycles over 1Ma were examined. A second scenario investigated the impact of the removal of surface geological material during each glacial cycle, considering i) uniform erosion over the entire surface of the domain, and ii) incision of a 100 m deep, 15 km wide valley located directly above the repository. The transport behavior of the low permeability, sedimentary geosphere was found to be robust, with virtually no changes in performance metrics for glaciation or erosion when compared to constant climate case with steady-state groundwater flow (Avis and Calder, 2015). Most recently, paleohydrogeogical simulations of groundwater flow and transport were conducted for a hypothetical sedimentary rock site as part an APM postclosure safety assessment (NWMO 2018).

Research to further understand the evolution (generation and preservation) of the underpressured conditions observed within the sedimentary rocks in southern Ontario began with several researchers considering compaction and dilation of the formations as result of glaciation as a result of load cycles from both ice weight and lithospheric flexure, including Normani and Sykes (2012), Neuzil and Provost (2014), Khader and Novakowski (2014). Nasir et al. (2013) examined the thermo-hydro-mechanical-chemical (THMC) response of sedimentary rocks of Ontario to past glaciations. Building on their earlier study, Neuzil (2015) proposed a general conceptual and quantitative hydrodynamic model invoking formation permeability, thickness, deformation properties, and rates of forcing to explain both the presence and absence of pressure anomalies observed in argillaceous formations around the world.

Normani et al. (2017) conducted numerical experiments to examine alternative scenarios for the cause of underpressures within the Ordovician formations in southern Ontario, including an examination of uncertainty related to glaciation scenarios, as well as uncertainty in initial heads prior to glaciation. The numerical experiments demonstrated that in addition to glaciation, other mechanisms such as exhumation can generate underpressures. In cases where underpressures pre-date glaciation (e.g. due to exhumation), these underpressures can be preserved through repeated cycles of glaciation. For this to occur however, vertical hydraulic conductivities must be lower than the measured values used in calculations where glaciation was considered as the sole mechanism for the underpressures. The numerical experiments also considered the presence of observed environmental tracers (e.g. helium) profiles that predate glaciation. Preservation of the helium profiles over time scales of 260 Ma also required that the vertical hydraulic conductivities be lower than the values determined as part of site characterization activities.

Although some evidence exists for a separate gas phase within the sedimentary formations where underpressures are observed, Beauheim (2013) notes that methane dissolved in porewaters within sedimentary formations may exsolve in a borehole, making its presence as a gas phase in the formation uncertain. The presence of a separate gas phase can dramatically decrease permeability to pore water and porewater pressure responses to clay rock deformation, or it may affect water pressure directly as a result of the large (e.g. tens of MPa, Intera 2011) capillary pressures present in clay rocks (Normani and Sykes 2012; Plampin and Neuzil 2018). Current research is focused on understanding whether the presence of gas itself can cause the observed underpressures, or whether it acts to facilitate or inhibit the development of underpressures.

As described above, expert resources and numerical modelling approaches for groundwater evolution developed through research program were applied as part of detailed site characterization activities for a proposed L&ILW repository in sedimentary rock in southern Ontario (e.g., Sykes et al. 2011; Normani et al. 2017). Application of these approaches is also planned as part of preliminary assessments in southern Ontario for the APM Project.

10.2.2 Geochemical and Redox Stability

An understanding of the geochemical and redox stability of groundwater systems at repository depths is developed by considering and integrating paleohydrogeological and hydrogeochemical evidence from site characterization activities (e.g. DGSM). This includes evidence for past geochemical alteration of the proposed host rock - in particular, evidence for changes in redox conditions over time, and evidence for past fluids from mineral infillings in the fractures. Tools and approaches developed and applied to support the integration and interpretation of site-specific geochemical data, including reactive transport modelling are described in the following sections. In the near-term, it is expected that this development will continue through the research program.

Information on the chemical and isotopic composition of groundwaters at a regional scale can be examined to develop an understanding of the geochemical evolution. For example, evidence for depth of penetration of waters with a cold-climate isotopic signature (i.e. glacial waters) within the region, and for redox conditions at depth, can be compared to site-specific data as part of geosynthesis activities.

As described in Section 9.3.1, a regional study of hydrogeochemistry in the sedimentary rocks of southern Ontario was conducted by Hobbs et al. (2011). This provided a framework for interpretation and integration of the information collected during detailed site characterization (e.g. NWMO 2011).

As documented in the Preliminary Assessments conducted as part of Phase 1 for the crystalline rock environments in northern Ontario and described in Section 9.3.1, there is very little information available on deep groundwaters at the regional scale. The most recent synthesis of information on waters within the crystalline rocks of the Canadian Shield is provided within Frape et al. (2004a).

10.2.2.1 Paleohydrogeological Evidence for Geochemical and Redox Stability

As described in Section 9.1.6, fracture minerals and alteration of the rock matrix provide evidence for geochemical evolution of a specific site during the past. This includes information on the chemical and isotopic composition of the fluids, the temperature of the fluids at the time of mineral precipitation (from measurements on fluid inclusions), and mineralogical evidence for alteration of redox sensitive elements, such as iron, within the fracture minerals or rock matrix.

McMurry and Ejeckam (2002) conducted a study within the WRA designed to look for mineralogical and geochemical indicators of the past depth of penetration of oxygenated, low-salinity waters potentially associated with recharge into the Lac Du Bonnet batholith during past glacial events. The isotopic composition and age of fracture filling minerals was also examined in a separate study and integrated to interpret the evolution of the groundwater flow system (Gascoyne et al. 2004). Most recently, a similar approach was applied as part of the Greenland Analogue study to examine evidence for past redox conditions from a deep borehole drilled directly in front of the ice sheet (Claesson Liljedahl et al. 2016). It was found that below the permafrost (at depths greater than 350 m), reducing conditions prevail in the study area. The presence of pyrite in fractures below approximately 50 m indicated that past penetration of dissolved oxygen in meltwaters has been limited in depth.

In sedimentary rocks, fluid inclusion studies were performed at the University of Bern, in collaboration with the University of Toronto. These studies involved petrographic examination of the vein and vug infilling mineral phase(s) from selected intervals (Devonian, Silurian and Ordovician) within cores from OPG's proposed L&ILW DGR project at the Bruce nuclear site near Tiverton, Ontario (Diamond et al. 2015; Diamond and Richter 2018). This collaborative research focused on evaluating the data for any meaningful interpretations about the timing of fluid movement in the sedimentary rocks at the Bruce nuclear site, as well as the nature (i.e., temperature and salinity) of the fluids. Results from Diamond and Richter (2018) demonstrated that the veins in the Devonian Bois Blanc Formation and Silurian Bass Islands formation appear to have had very similar histories to the Devonian Lucas Formation (Diamond et al. 2015). Celestine precipitated only in the Bass Islands samples, and a late generation of light oil + methane infiltrated only the Lucas Formation. Otherwise, the correlations between the nature of the fluids suggest that, in all three formations, vein calcite precipitated from a very low-salinity water (0.2–2.7 wt.% $NaCl_{equiv.}$) that was saturated in gas (presumably a CH_4–CO_2 mixture). Whereas calcite precipitated at 60 °C in the Lucas Formation, it precipitated at 78 °C in the ~100 m deeper Bois Blanc Formation.

An integrative study incorporating multiple sources of geochemical data was conducted (Petts et al. 2017). The purpose of the study was to assess the source of, and evolution of, fluid migration in the secondary porosity of the low permeability Ordovician carbonates situated on the eastern flank of the Michigan Basin beneath a site proposed for a L&ILW repository. The study focused on secondary mineral formation in the Cambrian and Ordovician rocks, incorporating the following components: i) fluid inclusion analyses of fracture-hosted calcite; ii) extensive C-, O- and Sr- isotopic characterization of secondary minerals in the Cambrian and Ordovician formations; and iii) integration of the fluid inclusion/geochemical data with the results of a successful U-Pb dating study of fracture infill calcites by LA-ICP-MS and ID-TIMS at the Jack Slattery Geochronology Laboratory, University of Toronto (Section 9.1.6).

The data were used to re-examine and refine a conceptual model for the fluid migration history in the 200-m thick Ordovician carbonate sequence. Key results of the integrated study indicate that: 1) multiple generations of secondary fracture minerals are evident from fluid inclusion data, suggestive of episodic fluid migration events; and 2) secondary mineral formation reflects a mixed fluid origin, including hydrothermal brines sourced from the underlying crystalline shield and/or from extensive fluid-rock interaction during transit in the Cambrian, as well as connate seawater. There was no evidence to suggest large-scale fluid migration through the Ordovician carbonates after the Silurian Period, despite evidence for orogeny-induced migration elsewhere in the Michigan Basin. This strongly suggests that the low permeabilities in the carbonates at the site (i.e., hydraulic conductivities $<10^{-11}$ m sec^{-1}) were established early in the evolution of the system. The overall findings of this integrative study (Petts et al. 2017) support the long-standing conclusion that the deep sedimentary formations beneath the Bruce nuclear site comprise an aquiclude system, in which solute migration is diffusive, and effectively has been isolated from the shallow environment for hundreds of millions of years.

10.2.2.2 Numerical Modelling Approaches to Assess Geochemical and Redox Stability

Using geochemical modelling, McMurry (2000) conducted a case study to develop an improved understanding of how groundwater compositions within crystalline rock of the Lac Du Bonnet batholith would evolve in response to deep recharge by a low salinity, oxidizing meltwater. The evolution of groundwater compositions can also be examined using reactive transport modelling to assess: 1) the degree to which dissolved oxygen may be attenuated in the recharge region of the proposed host rock; 2) how geochemical reactions (e.g., dissolution-precipitation, oxidation-reduction, and ion exchange reactions) may affect groundwater salinity (density) along flow paths; and 3) how diffusion of reactive solutes may evolve in the porewaters of low-permeability geological formations.

MacQuarrie and Mayer (2003) conducted a state-of-science review on the application of reactive transport modelling to fractured crystalline rock. Following on recommendations from that review, the multi-component reactive transport code MIN3P was employed to investigate redox processes in fractured crystalline rocks using two simplified base cases (a single fracture case and a single fracture zone case) in which vertical groundwater flow was assumed to a depth of 500 m (Spiessl et al. 2009). Sensitivity analyses were also conducted. MacQuarrie et al. (2010) examined different conceptual models for oxygen penetration and consumption in fractured crystalline rock, and demonstrated the strong dependence of modelling results on the conceptual model employed. Trinchero et al. (2018) recently demonstrated the application of a numerical interface between DarcyTools and PFLOTRAN to carry out site-scale reactive transport calculations of oxygen ingress into fractured crystalline rock of the Forsmark site, Sweden. In the near-term, an investigation of numerical tools which could potentially be applied to conduct similar, site-specific analyses in crystalline rock in support of geosynthesis activities is planned.

A state-of-science review for the application of reactive transport modelling to sedimentary rocks was conducted by Mayer and MacQuarrie (2007). Following MIN3P code enhancements, Bea et al. (2011, 2015) used MIN3P to simulate flow and transport in a hypothetical, two-dimensional sedimentary basin subjected to a simplified glaciation scenario (a single cycle of ice sheet advance and retreat). Further code enhancements were made to improve the capabilities of MIN3P for reactive transport modelling in low permeability media, leading to a new version of the code (MIN3P-THCm; Xie et al. 2015). This version of MIN3P was also parallelized, as described in Su et al. (2015). The enhanced code was applied to investigate the formation mechanisms for sulfur water observed in the Michigan Basin (Xie et al. 2018). The salinity-dependent sulfate reduction model provides a possible explanation for the observations by Carter (2012) that sulfur water exists at intermediate depths, but not in the deep subsurface (Xie et al., 2018).

Further development and evaluation of code capabilities for large scale 3D flow and reactive transport problems, as well as extension of reactive transport simulations on the formation of sulphuric waters in sedimentary basins subjected to a glaciation/deglaciation cycle is on-going within the research program. A generalized formulation for heat transport and the temperature-dependence of chemical reactions based on empirical experimental data will also be implemented.

In the near-term, the use of geochemical and sorption modelling will be explored through the research program as a tool to estimate the uncertainties in sorption coefficients (K_d) values due to groundwater evolution with time, and to validate measured K_d values for key radionuclides.

10.3 Seismicity

The regions currently in the site selection process are either in a crystalline rock setting within the Canadian Shield in northern Ontario, or in sedimentary rock setting within the Michigan Basin in southern Ontario. Both settings are located within the centre of the stable North America craton, and are currently characterized by low levels of seismic activity (Ackerley et al., 2019). Large earthquakes are infrequent, with contemporary seismicity occurring along pre-existing zones of weakness (e.g. fractures, fracture zones or faults). Damage to intact rock is not likely to occur, because in-situ tectonic and glacially-induced stresses are not considered sufficient to generate the forces required to create new ruptures within intact rock (Lund 2006). In the far future, an increase in the number and intensity of earthquakes is likely in response to the reduction in loading as ice sheets retreat (see also Section 10.3.3).

Earthquakes typically are far less destructive at depth than at the surface, diminishing the impact of any seismic activity on a deep geological repository (Bäckblom and Munier 2002). In seismic hazard analyses (Section 10.3.1), the equations used to predict ground-motion apply to sites on the Earth's surface. Information on the relationship between motions underground during an earthquake and those on surface is therefore required, in order to extend seismic hazard analyses underground. The Polaris Underground Project (PUPS) was conducted at the Sudbury Neutrino Observatory to determine how ground motions recorded underground compare with those located on similar hard rock (glaciated norite and grantic rocks) at the Earth's surface (Atikinson and Kraeva 2011). Results from PUPS demonstrate that, in general, earthquake ground motions underground are lower in amplitude than those on the surface. The ratio of surface/underground motion was found to be a frequency dependent function that depends on the type of earthquake and the depth of the underground cavern. Another important conclusion from the results of PUPS was regarding the attenuation of ground motion near the earthquake source, which showed that there is a relatively steep attenuation of wave amplitudes moving away from an earthquake source, implying that this is a mitigating factor to be considered in seismic hazard studies in Ontario (Atkinson and Kraeva 2011).

The final site selected for a repository will be located away from large fracture zones, and containers would be placed in back-filled rooms without significant local fractures. The low magnitude earthquakes observed to occur more frequently are unlikely to have significant effect on the site, repository or containers. Recent studies to examine the potential effect of rare, higher magnitude earthquakes on the long-term stability of a repository are discussed further in Section 10.4.2.

10.3.1 Seismic Hazard Risk

Seismic risk will be assessed during site characterization activities by conducting seismic hazard assessments (e.g. AMEX GEOMATRIX 2011). In a seismic hazard assessment, a seismic source model consisting of large regional source zones is generated and used to simulate the occurrence of earthquake activity. Characterization of the seismic source provides a model for the rate of occurrence, spatial distribution and size distribution of earthquakes surrounding the site. Within the research program, current activities to support future seismic hazard assessments include maintaining the Canadian Hazards Information Service (CHIS) network of seismographs to monitor seismic activity in Northern Ontario and eastern Manitoba (Section 10.3.2). This will be supplemented with information on lower magnitude earthquakes from microseismographs established in the siting area as part of site investigation activities; and paleoseismic investigations of soft sediment (lake bed) deformation in regional watersheds (Section 10.3.3).

In the near term, a review of Seismic Hazard Assessment approaches for low-seismicity regions will be completed to assess options for site-specific studies. Seismic hazard assessments will be conducted to support licence applications following the detailed characterization, construction and operation phases of the repository life-cycle.

10.3.2 Regional Seismic Monitoring

The Canadian Hazards Information Service (CHIS) of Natural Resources Canada provides seismic monitoring across Canada. The NWMO has specifically supported monitoring in northern Ontario, through assisting in the installation and maintenance of seismograph stations which extend the ability of the network to detect lower magnitude events and to provide a more accurate assessment of their location and magnitude. The objective of this work is to document the background seismicity in order to support future seismic hazard assessments, as discussed in the previous section.

All the stations are operated and maintained by CHIS, as part of the Canadian National Seismograph Network. For example, Figure 10-1 shows seismic events recorded in 2017 in eastern Canada. The NWMO has also supported the development of an improved regional seismic network in southern Ontario. There, the existing CHIS network has been enhanced through 3 seismograph stations installed regionally and supported now by OPG as part their proposed L&ILW DGR project in southern Ontario.

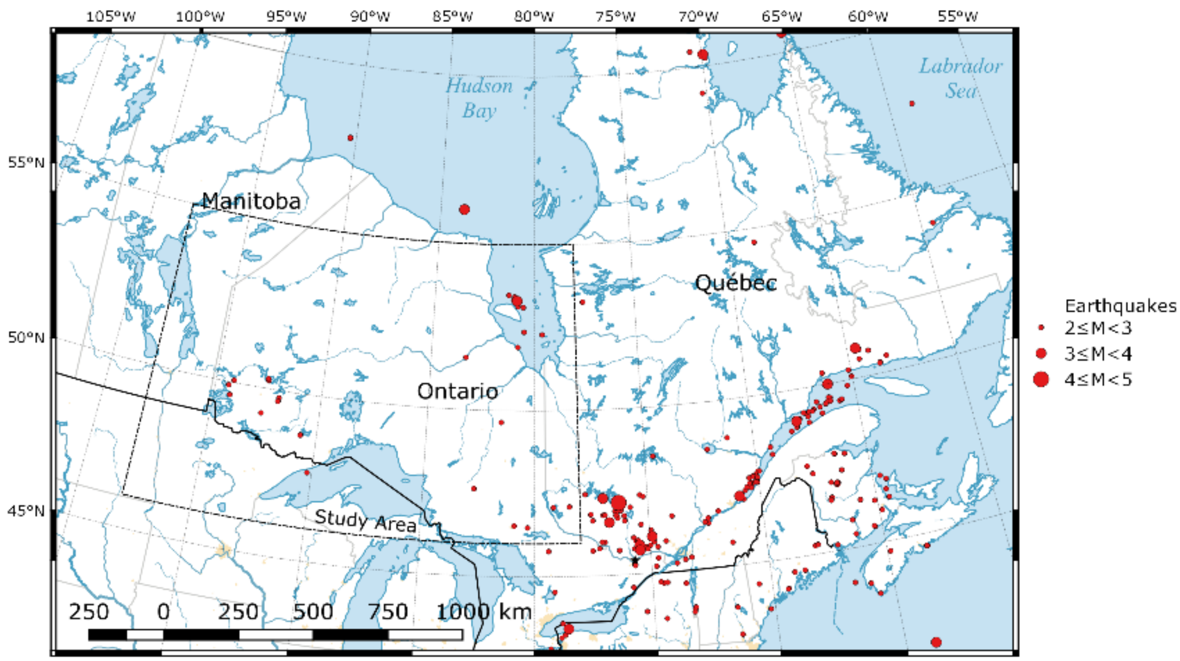
As part of site assessments, a local monitoring network will be established to capture lower magnitude (microseismic) events in the specific repository areas. By examining the spatial distribution of low magnitude seismic events in a siting area (if present), structural anisotropy may be identified. Once a site has been selected, monitoring of microseismic events would continue through detailed characterization and beyond through the site preparation and construction, operations and extended monitoring and could extend through decommissioning to the post-closure phase. This work will be described in the site characterization plan and geosphere monitoring plans prepared for the selected site as part of site investigations. Together within information from the Canadian National Seismograph Network, the microseismic monitoring data will form the basis for future seismic hazard assessments conducted in support of license applications.

10.3.3 Paleoseismicity

Given the life-cycle of a repository, potential perturbations from rare strong earthquakes ground motions 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.

Sims (2012) conducted a state-of-science review of the paleoseismological methods used to support seismic hazard assessments. The review identified that the method most successfully applied in both the eastern United States and Canada is reconnaissance of river, stream and lake banks for paleoliquefaction structures.

a)



b)

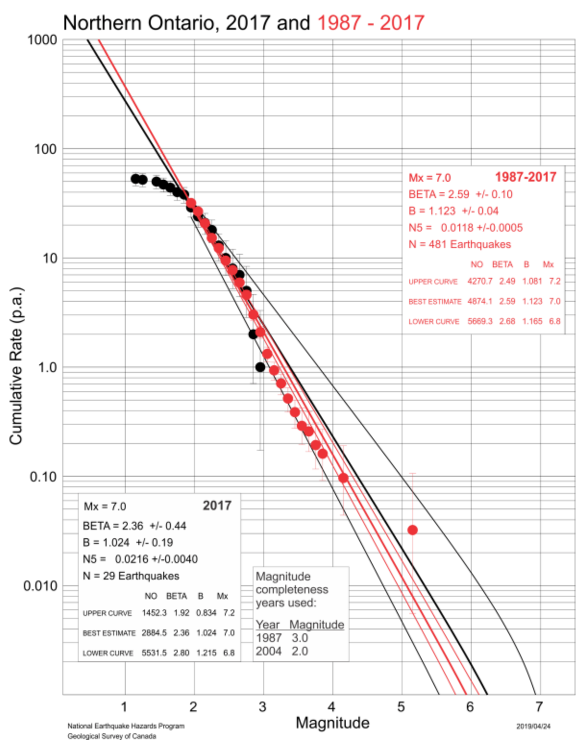


Figure 10-1: (a) Earthquakes in eastern Canada, 2017; (b) Recurrence curves for Northern Ontario, 2017 and 1987–2017 (Ackerley et al. 2019).

In northern Ontario, fine-grained lacustrine deposits of Pleistocene and Holocene age were identified as being of primary interest. In southern Ontario, Sims (2012) identified specific sections of the Grand River, the Thames River and the Maitland River as the primary focus.

In the sedimentary rocks of southern Ontario, a neotectonics assessment was completed in support of OPG's proposed L&ILW DGR project (Slattery 2011). Desktop and field based methods were used to look for evidence of paleoseismicity within Quaternary sedimentary deposits in the region, within a 5 km zone and a 50 km zone around the proposed site. The investigation was conducted in three phases, beginning with a desktop study, follow by the interpretation of air photographs (viewed in stereo) to assess the occurrence of neotectonic features and/or landforms, and finally field-based inspection of the potential neotectonic features and/or landforms identified in the first two phases of study. In addition, detailed structural mapping of Devonian-aged outcrops exposed on the Lake Huron shoreline was conducted in a separate, complementary study by Cruden (2011). As part of site-specific studies, a similar neotectonic assessment and structural mapping field work will be conducted as part of the neotectonics and paleoseismology component of site characterization work, as defined in the site chararcterization plan for the selected site.

Another direction of research on past earthquakes is to look for evidence of fault reactivation. A particular example of fault reactivation is the Pärvie fault in northern Sweden, which displays offsets of up to 10 m over distances of 150 km subsequent to the last glaciation (Lundquist and Lagerbäck 1976; Lagerbäck and Sundh 2008; Lindblom et al. 2015). In the Canadian Shield, the only known surface rupture was observed at Ungava, northern Quebec, from a M6.3 earthquake in 1989. The event resulted in up to 3 m offset at ground surface of an existing fault over a distance of 7 km (Adams 1989). There is no evidence of surface rupture within Ontario, and no identified structures can be conclusively linked to postglacial reactivation (Fenton 1994). During site characterization, outcrop fracture mapping will be conducted look for evidence of fault reactivation. High-resolution, LiDAR-derived, digital elevation models may also be used to identify new post-glacial fault scarps and to refine scarps previously mapped by aerial photographic interpretation, as was done in northern Sweden by Mikko et al. (2015).

Through paleoseimic studies, the mapping and identification of submarine landslides within lake-bottom sediments at the regional watershed scale are used to improve knowledge of seismic hazard. Several paleoseismic studies have employed sub-bottom acoustic profiling using a high-density line spacing to construct a pseudo-three-dimensional seismo-stratigraphy of lake deposits (e.g. Schnellman et al. 2002; 2006; Monecke et al. 2006; Strasser et al. 2006; 2013; Moernaut et al. 2009). Building on this earlier work, the Geologic Survey of Canada documented an integrated seismo- and chrono-stratigraphic methodology for the investigation of (paleo)earthquake signatures preserved in freshwater lake deposits in Canada (Brooks 2015; 2017). A watershed region on the Canadian Shield near the Rouyn-Noranda, in northwestern Quebec, was selected to explore and demonstrate this methodology. The work involved two steps: i) mapping of landslide deposits using a sub-bottom acoustic profiling system to produce 2-dimensional geophysical images of the sub-bottom in Duparquet and Dufresnoy lakes; and ii) collection of the lake-bottom sediment cores from the frozen surfaces of the lakes (Brooks 2016, 2018). These latter core samples were used to date the landslide events primarily by analyzing the thickness pattern of varved sediments that either overlie or are interbedded with the landslide deposits. The compilation of the results from these two studies identified 11 interpreted paleoearthquakes which occurred between approximately 9400 and 8900 years before present, likely during a period of rapid crustal unloading at the time of last glacial retreat and presence of post-glacial Lake Ojibway (Brooks 2018).

NWMO continues to support research conducted by the Geological Survey of Canada (NRCan) to investigate the occurrence of historic earthquakes by studying disturbed sediments in lake basins, as an analogue for the magnitude and frequency of events which may be experienced at a repository location. It is expected that this integrated methodology will be applied as part of a complimentary study in the region surrounding the selected siting area and described in the site characterization plan. In the near-term, within the research program, potential approaches to integrate the information from paleoseismological studies with the recurrence curves developed through seismic monitoring will be investigated, for use in future, site-specific SHAs.

10.4 Geomechanical Stability of the Repository

In this section, research designed assess the factors and processes that affect the geomechanical stability of the repository is described. The change in rock properties as a result of creating an opening in the rock during construction are considered in Section 10.4.1, and the long-term evolution of the repository considering both potential for fault rupturing and coupled Thermal-Hydraulic-Mechanical processes is described in Section 10.4.2 and 10.4.3, respectively.

10.4.1 Excavation Damaged Zones

The Excavation Damaged Zone (EDZ) is a region of damaged or disturbed rock that extends several meters outward from an excavated underground opening as a result of stress re-distribution within the rock mass. The EDZ can lead to the development of interconnected, higher permeability zones which are potential pathways for fluid flow and mass transport within a repository. Effective and reliable prediction, characterization and treatment of the EDZ is necessary for (1) design and construction of a DGR; and (2) developing the safety case for its long-term performance.

Historically, brittle rock mass behaviour and EDZ formation in crystalline settings were studied at the AECL URL and the Äspö hard rock laboratory in Sweden (Martin 1993; Martin 1997; Read 2004; Martino and Chandler 2004; Diederichs 2007). Experience from geoscientific studies of the Excavation Damaged and Disturbed Zones in sedimentary rocks were summarized by Fracture Systems Ltd. (2011). In the near-term, a similar, state-of-science review of EDZ in crystalline rocks will be initiated through the research program.

Subsequently, NWMO has sponsored EDZ research to further enhance scientific understanding of the EDZ mechanics, verification, and mitigation in both crystalline and sedimentary rocks. Based on the results of trials conducted in the UDF (see Section 12.5.3), an excavation method will be chosen to minimize the extent of the EDZ. The research programs cover (1) development of numerical modelling methodologies for EDZ delineation; (2) field characterization of EDZ; (3) back-analysis of field monitoring studies; (4) potential design measures to minimize or effectively cut-off the EDZ; and (5) experimental programs related to rock mechanics testing and constitutive model development (as discussed in Section 9.5.4).

10.4.1.1 Numerical Model Developments

Several zones are present within the EDZ, which have different characteristics. Following the terminologies defined by Tsang et al. (2005), Fracture Systems Ltd. (2011) and updated by Diederichs et al. (2014) and illustrated in Figure 10-2, the EDZ consists of:

- The Excavation Disturbed Zone (EdZ) where elastic strains occur and the stresses deviate from the pre-excavation conditions. This is a zone with hydromechanical and geochemical modifications, without major changes in flow and transport properties.

  The Excavation Damaged Zone (EDZ) is a zone with hydromechanical and geochemical modifications including significant changes (one or more orders of magnitude increase) in flow and transport properties. This abbreviation is used in general literature to include the inner and outer EDZ and the HDZ (as defined below).

- Outer Excavation Damage Zone (EDZ_o) where distributed micro-fractures increase in frequency moving towards the excavation boundary and are identified by volumetric contraction numerically.

- Inner Excavation Damage Zone (EDZ_i) where increased fracture connectivity occurs toward the excavation boundary and is identified by volumetric extension numerically.

- Highly Damaged Zone (HDZ) where discrete macro-fractures occur and are identified by low stress concentration numerically.

- Construction Damage Zone (CDZ) where fractures are entirely the result of construction technique used and overlap those within the HDZ.

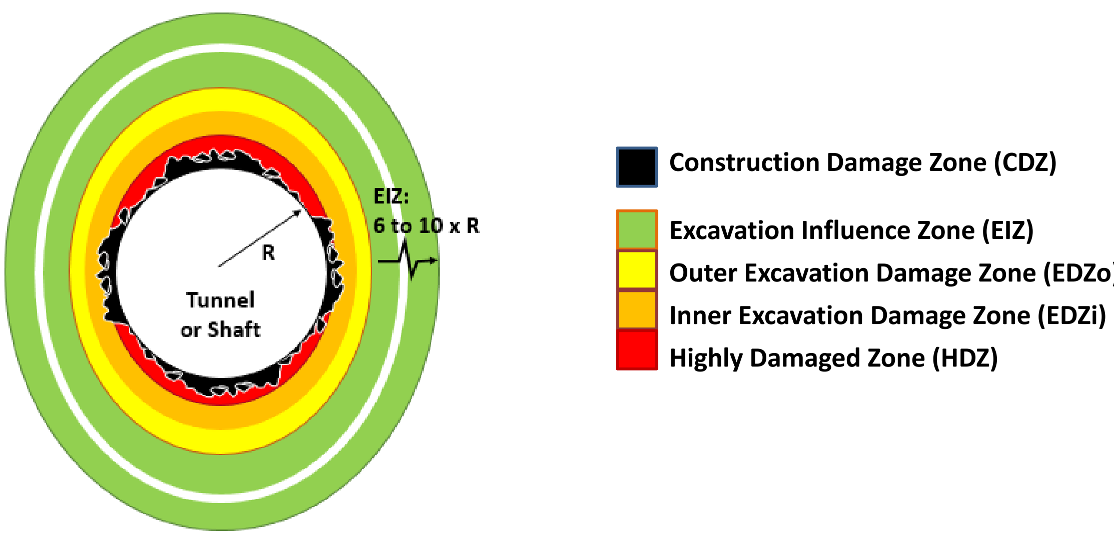


Figure 10-2: Illustration of different zones within the EDZ (from Diederichs et al. 2019).

Queen’s University has been investigating the effectiveness of the three main numerical modeling approaches for EDZ modelling; i.e., continuum, discontinuum, and hybrid methods.

In the continuum analyses, two different constitutive models were used for prediction of EDZ dimensions: the Damage Initiation and Spalling Limit (DISL) model of Diederichs (2007) and the Cohesion Weakening Friction Strengthening (CWFS) model proposed by Hadjiabdolmajid et al. (2002). The dilation model of Walton and Diederichs (2014) provides input parameters to the brittle damage simulation based on the CWFS model. Using continuum modelling, the numerical dimensions of the EDZs were determined in three rock types (granite, limestone, shale) under various in-situ stress conditions. Empirical correlations were proposed for the minimum and maximum numerical dimensions of the EDZs (Diederichs et al. 2014, Perras and Diederichs 2016). Further research examined the influence of the natural variability present within the rock mass on prediction of EDZ by a reliability-based design method in conjunction with continuum modelling (Diederichs et al. 2019).

Some of the early discontinuum modelling research included stability analysis of a tunnel in a blocky rock mass by Fekete and Diederichs (2012). Ongoing research is studying reliability assessment in brittle damage prediction using continuum and discontinuum approaches.

Various hybrid Finite-Discrete-Element models were applied to predict EDZ formation observed around deep tunnels within massive rock masses. For example, the modelling by Vazaios et al. (2019) accurately matched the observed EDZ around the AECL URL test tunnel.

In the near-term, EDZ modelling will focus on further advancing numerical methods such as Discrete Element Method (DEM), hybrid modelling (Finite-Discrete-Element Method, FDEM), and THM modelling. In particular, the research program will attempt to combine coupled THM model continuum, discontinuum, and hybrid models. Several potential modelling objectives will include studying the effect of strength degradation of rock on EDZ, impact of different time-dependent deformation models on short-term and long-term excavation response, and effects of pre-existing fractures and induced damage on fluid flow in EDZ using discontinuum models.

10.4.1.2 In-situ Deformation Mapping, EDZ Detection and Back-Analysis

Characterization of the geomechanical properties of the EDZs is achieved by conducting “mine-by” experiments or by monitoring of their evolution with time. Geotechnical, hydraulic, and geophysical measurement methods are used to characterize the extent and properties of the EDZs during and after excavation of an underground opening.

NWMO has been assessing the ability of various in-situ techniques (detailed mapping of fractures within slabs cut from a tunnel wall, geophysical surveys, extensometers, photogrammetry) to monitor rock deformation and characterize EDZ following excavation of underground openings, and the numerical back-analyses of this field monitoring data. This research has demonstrated that it is numerically possible to back analyze field data and predict deformations and stresses in the rock mass; some examples are provided below.

To increase understanding of the EDZ and in particular, to explore the possible existence of a continuous EDZ along a deposition tunnel, Olsson et al. (2009) examined the fracturing in a tunnel within the Äspö Hard Rock (diorite) Laboratory in Sweden. The experiment involved drilling and sawing of blocks of rock from the tunnel wall in which fractures (natural, blast and blast-induced fractures), were photographed, digitized and then 3D modelling of the fractures was conducted. Key conclusions from the study were: i) no evidence of a continuous EDZ was found in the investigated area; ii) blasting fractures were found to be strongly influenced by the presence of natural fractures; and iii) because blasting fractures do not form a continuous network, longer, natural fractures are the key control on potential water flow in the rock mass.

Geophysical surveys were used to detect EDZ fractures within the Äspö Hard Rock Laboratory. Earth Resistivity (RES), Induced Polarization (IP), and Ground Penetrating Radar (GPR) data were collected; Light Detection and Ranging (LiDAR) data were collected as a reference for surface structures, surface topography, and site geology. Based on an analysis of the data, the HDZ was found to be approximately 5 to 10 cm in thickness and the EDZ was detected between 15 and 35 cm below the excavation surface. Two-dimensional RES profiling generated the most reliable assessment of the HDZ, whereas GPR data were more useful in the estimation of the EDZ dimensions (Diederichs et al. 2019).

In another study, pillar deformation data from the Creighton mine in Sudbury, Ontario was analyzed - one of the ten deepest mines in the world with mining at 2.4 km depth. The data were collected by Multi-Point-Borehole-Extensometers (MPBXs) used to record deformation of the rock mass caused by excavation of tunnels at 2.4 km depth. The granite in the area is relatively massive to moderately jointed and under high in-situ stresses that posed risks of severe stress-induced damage and strain-bursting for excavation work. Back-analyses of the field data with continuum modelling (as described Section 10.4.1.1) were successful in simulating the progressive pillar yield mechanism (Diederichs et al. 2019).

Ongoing and future research will (1) further improve our understanding of EDZ formation and characterization and (2) develop methods to predict EDZ in rocks which will then be verified in the demonstration area within the UDF. As discussed in Section 9.6.3, NWMO will also explore the possibility of back-analyzing of the data from GC-A experiment of the Mont Terri Project to characterize the development of the EDZ within the Opalinus Clay at the URL in Switzerland.

During site characterization activities, site-specific information on ground stresses and mechanical properties of the host rock will become available. These data will be incorporated into the various assessments, together with appropriate allowances for residual uncertainties. With respect to the post-closure performance of a repository, the enhanced permeability of the EDZ is of particular interest. Research on the EDZ is expected to continue through the site preparation and construction phase, with geoscientific verification activities to be conducted in the UDF.

10.4.1.3 EDZ Mitigation

Although it may not be practical to eliminate the EDZs around key locations within a repository (e.g. tunnel or shafts), excavations can be designed in a manner which limits their extents. Furthermore, after backfilling of the rooms, swelling pressure from bentonite backfill may suppress further development of the EDZ. In both crystalline and sedimentary rock settings, methods to minimize the effects or cut-off the EDZ have been developed and tested (e.g. Martino and Chandler 2004; Delay et al. 2007).

Research conducted by York University (formerly at ETH in Zürich, Switzerland) is underway to develop improved mitigation strategies considering different excavation and seal geometries. Numerical simulations are used to optimize cut-off system for passive EDZ sealing, and to develop nomograms (design graphs) for a broad range of geological settings, including crystalline and sedimentary rocks (Sharma et al. 2019).

Research on mitigation measures will continue through the site preparation and construction phase, with demonstration and/or geoscientific verification experiments conducted within the UDF.

10.4.2 Repository Design Considerations - Fault Rupturing

In the event of an earthquake, slip may occur on fractures within the repository. Therefore, it is imperative to identify the characteristics of faults and discrete fracture networks which are required to numerically model the fault re-activation process and quantify the consequences on the UFCs integrity.

To ensure that the performance of a repository will not be affected by off-fault fracture movement, a respect distance must be maintained in a deep geological repository design. This distance is determined from the criterion that outside the respect distance from the fault, no off-fault fractures intersecting the placement room (and potentially intersecting UFCs) will undergo a cumulative shear displacement that could compromise a barrier system.

NWMO recently conducted a study to numerically simulate a sizable seismic event resulting in the mobilization of surrounding fracture networks. Rupture of a seismogenic fault and its effect on the deformation of the off-fault fractures were examined. The purpose of the analysis was to determine the off-fault fracture displacements to inform the selection of respect distance within the repository horizon in crystalline rock (ITASCA 2019a).

Three different models were constructed to accommodate the fault size for moment magnitudes (Mw) of 6.1, 6.6 and 6.9 seismic events occurring at the end of the glacial cycle when the vertical stress due to ice sheet is zero but glacially-induced horizontal stresses still remain. This base case analysis was conducted for five DFN realizations developed from the structural geology of Forsmark, Sweden. The modelling results revealed that for an earthquake with a moment magnitude, Mw of 6.1 and a dip angle of 40° (base case), the fault average shear displacement during the slip is about 1.6 m and the maximum shear displacement along the fault is 3.4 m. No DFN fractures slip more than 5 cm were observed in all DFN realizations except for a fault dip angle of 30°. Increasing the event magnitude while maintaining a dip angle of 40° (base case) resulted in a greater number of off-fault fractures with slippage over the 5 cm criterion and an increase in the distance to the fractures with such large displacements. Once site-specific DFN information is available, similar analyses will be conducted to support repository engineering and design, as part of a complementary study during detailed site characterization.

New and alternative rupture models for the Forsmark site in Sweden and to Olkiluoto site in Finland were recently reported by Hökmark et al. (2019). A main conclusion from this work is that the critical radii (the radii of the smallest fractures which must be avoided when determining the position of canisters), increase confidence in the conservative nature of the rules used in the layout for the repository at Forsmark.

A literature review to summarize the current state-of-practice in the area of fault-slip events in crystalline rock of the Canadian Shield is on-going within the research program.

10.4.3 THM Analysis of Shaft and Cavern Stability

The excavation of the underground openings (i.e. including placement rooms, shafts) for a repository, and the subsequent backfilling with heat-emitting UFCs as well as the buffer material, will induce coupled THM processes in-situ. Consequently, the performance of the rock mass, particularly in the near-field around the repository during the heated period, requires consideration of a range of processes from thermal to hydraulic to mechanical. Canadian numerical models that include these processes have ranged from MOTIF in the past (developed by AECL), to current COMSOL and FLAC/UDEC based models. These codes are tested and improved through application to scale experiments or international comparisons, such as the DECOVALEX project (see Section 10.2.1).

NWMO has been conducting numerical analyses at near- and far-field scales to enhance our understanding of the response of the rock mass to hypothetical Canadian DGR configurations in both sedimentary and crystalline settings (ITASCA 2015; 2019b). These studies considered perturbations induced by the repository as well as the natural processes expected during a 1 Ma period. In the study by ITASCA (2015), the THM processes were one-way coupled, whereas ITASCA (2019b) employed fully coupled THM analyses using refined input parameters. The sensitivity of the model predictions to some uncertain model input parameters (e.g. block-to-contact stiffness ratio for discontinuum modelling, poroelastic properties, and rock mass permeability) were also investigated.

All THM analyses were conducted for placement rooms consistent with the current conceptual APM repository design with 48-bundle canisters. THM modelling was conducted at two scales; near- and far-field scales, using a 3D continuum numerical code (FLAC3D) to generate evolving temperature, pore pressure, stress and deformation fields in the rock mass. In addition, 2D and 3D discrete element modeling was performed using UDEC and 3DEC to simulate evolution of damage around the repository rooms (i.e. near-field scale).

A number of conservative assumptions regarding geomechanical conditions were introduced in these analyses in order to provide bounding solutions for the various scenarios, including: time-dependent strength degradation; glaciations; low-probability seismic ground shaking; saturated rock mass and bentonite buffer. The effects of combinations of these loads and perturbations were also examined.

As site characterization progresses, site-specific information will be used to select model input parameters for the analysis of long-term repository stability using the methodologies developed through the research program, as described above. NWMO continues to monitor advances in the area of coupled THM analysis pertinent to long-term stability of DGR in both sedimentary and crystalline rock settings. In the near-term, back-analysis of coupled THM processes from Mont Terri FE-M experiment will be completed through a working group led by Nagra.

10.5 Geoscientific Studies in Support of Geosynthesis

In this section, additional geoscientific studies on topics relevant to long-term evolution which may be required to support the geosynthesis for a specific repository site are described. Many of these studies involve collection and interpretation of information at a regional scale. The complementary studies to be completed at a specific site will be identified within the site characterization plan.

10.5.1 Natural Resources Assessment

The absence of economic natural resources was one of the many factors addressed when assessing the potential suitability of both crystalline and sedimentary sites. During site characterization activities, the absence of economic resources will be further examined during borehole investigations(including core sampling, analytics), data assessment and reporting, as described in the site characterization plan. For example, through the detailed site characterization activities conducted for OPG's proposed L&ILW DGR project, it was demonstrated that commercially viable oil and gas reserves are not present (NWMO 2011; Engelder 2011).

Through the research program, the Geological Survey of Canada conducted a quantitative assessment of oil and gas resources in self-sourced and self-retained shales of the Collingwood and Rouge River members of the sedimentary sequence in southern Ontario (Chen et al. 2019). This study concluded that only a small proportion of potential hydrocarbon resources lies within the Huron Domain, where NWMO has some communities involved in the site selection process. Chen et al. (2019) reported that the bulk of the potential hydrocarbons estimated to be trapped within the members examined is exceptionally low, due to several factors including (but not limited to): low permeability, low formation pressures, low degrees of thermal maturation and poor oil show index (S1/TOC<1).

10.5.2 Karst Assessment

The sedimentary rock sequence below southern Ontario includes soluble rocks such as carbonates and evaporites. Where erosion of these rocks by dissolution occurs, enhanced permeability is created through a process referred to as karstification. To support the interpretation of site-specific hydrogeological data collected as part of site characterization activities, Worthington (2011) conducted an assessment of the distribution of karst at and beneath the site for OPG's proposed L&ILW DGR.

If a sedimentary rock site is selected as a potential site for the APM repository, a similar karst assessment may be required to support interpretation and synthesis of geological and hydrogeological information. This would be conducted as a complementary study and described in the site characterization plan.

10.5.3 Shale Cap Rock Barrier Integrity

Engelder (2011) conducted a study on shales from the Appalachian-Ouachita stratigraphic system as an analogue to demonstrate the long-term integrity of the ~200 m thick Upper Ordovician shale sequence at the proposed site for OPG's L&ILW DGR. This shale sequence would act as the primary cap rock seal for a DGR located within the Cobourg Formation. The findings of the study were used to demonstrate that the integrity of the Upper Ordovician shales can be maintained over geological time (Engelder 2011).

10.6 Research Program Summary

Research to advance process understanding and to maintain academic expertise on long-term geosphere stability is expected to continue through to the decommissioning phase. Specific research areas of focus during the different phases of the repository life-cycle are given below.

Site Selection and Characterization Phase

During this phase, numerical methods and approaches to describe and evaluate the evolution of the geosphere over the long-term are being applied in support of the preliminary site investigations currently underway. This includes the determination of plausible surface boundary conditions during glaciation, which can be used in paleohydrogeological simulations of the site to examine groundwater flow and transport. A state-of science review of glacial erosion in crystalline rocks will also be completed to support geosynthesis activities.

Research programs will continue to advance process understanding related to glaciation, including continental-scale glacial modelling, erosion, and glacial and proglacial environments. In the near term, reactive transport modelling tools and approaches to assess geochemical and redox stability in crystalline rocks will be investigated. Support for seismic monitoring in northern Ontario will continue, while microseismic monitoring at potential sites will be conducted as part of on-going site investigations. Paleoseismic methods will be applied to the region of the selected site, as a complementary study to support geosynthesis activities. In support of future site-specific seismic hazard assessments, potential approaches to integrate the information from paleoseismological studies with the recurrence curves developed through seismic monitoring, will be investigated.

Research to support assessments of the geomechanical stability of a repository over the long term will advance numerical methods to predict EDZ and on potential mitigation (cut-off and backpressure from swelling bentonite) designs. Complementary studies to assess the long-term geomechanical stability of the repository, including THM analyses of shaft and cavern stability and the potential impact of fault-rupturing, will be conducted as part of detailed site characterization activities and described in the site characterization plan. Any other complementary studies to support the geosynthesis for the selected site will also be conducted during this phase.

Site Preparation and Construction Phase

In this phase, the aim is to continue to advance process understanding and maintain university-based expertise related to long-term evolution of the geosphere, including glaciation, deep groundwater stability (including both transport and geochemical stability), seismicity and geomechanical stability.

Operations and Extended Monitoring Phase

Monitoring advances in process understanding and maintaining university-based expertise related to long-term evolution of the geosphere, with a particular focus on glaciation and seismicity, are anticipated to be the main activities during this phase. These activities will then support a licence application to decommission the repository.

Decommissioning and post-closure phase

It is envisioned that there may be a need to maintain university-based expertise on specific topics related to the long-term evolution of the geosphere during this phase. These will be identified in the future, as the APM project advances.

Major Facilities

No major facilities are required. It is envisioned that the research describe above will continue to be conducted in University environments or through international collaborations in underground research projects.

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11 BIOSPHERE

This section discusses the plans for biosphere research in support of safety assessment. The focus is on potential contaminant transport in the surface environment and exposure pathways relevant to the safety assessment of a deep geological repository.

The biosphere program is described here in the following topic areas:

- General Approach;
- Terrestrial Environment;
- Aquatic Environment;
- Atmosphere;
- Long-term Biosphere Evolution;
- Human Behaviour; and
- Biota.

11.1 General Approach

The biosphere is a complex system, and will change over the one million year timescales considered in a safety assessment. From an NWMO safety assessment perspective, the approach is to simplify the system enough to obtain a useful estimate of the potential dose and non-radiological consequences through consideration of dominant or representative pathways.

Current models are based on treating the biosphere as a series of compartments representing different “pools” for contaminants. Transfer between some pools is explicitly modelled, while others are modelled by ratios that assume the compartments are in quasi-equilbrium over the time scales of interest.

This approach applies to preclosure and postclosure assessments and is consistent with Canadian guidelines for assessing nuclear power plant emissions, notably CSA N288.2-M91 (CSA 2003) and CSA N288.1-14 (CSA 2014). Similar approaches are used by other national waste management organizations in their main safety assessment models.

NWMO will continue to develop improved preclosure and postclosure models consistent with developments in software and in hardware, and increased knowledge from the supporting technical research programs described in other sections. Participation in international experiments and collaborative programs (such as BIOPROTA and MODARIA) will also continue with a view to improving understanding of biosphere and obtaining data for computer modelling and validation. Ultimately, site specific models will be compared with results from the site characterization activities to enhance or confirm confidence in these models.

11.1.1 Preclosure Biosphere Modelling and Data

The preclosure period includes site preparation, construction, operation, decommissioning, monitoring and closure. Much of the preclosure biosphere characterization, modelling, assessments and data will be detailed in the environmental assessment and are not discussed in this plan. This section will focus on elements of the the biosphere captured in the preclosure safety assessment (Section 14.1).

The preclosure safety assessment employs an environmental transfer model to calculate potential dose to the public from the airborne releases from a nuclear facility under normal and accident conditions (Liberda and Leung 2018). Canadian Standards Association (CSA 2003) is the primary model and data reference for the preclosure biosphere assessment. Depending on the site location, additional site-specific data may be needed. This data would be acquired in the context of site characterization, e.g. installation of a meteorology tower. Other data collected in support of postclosure biosphere modelling will be evaluated for relevance to the preclosure biosphere and used if appropriate.

11.1.2 Postclosure Biosphere Modelling and Data

The postclosure biosphere is currently modelled using SYVAC3-CC4 (NWMO 2012). The NWMO is currently developing an AMBER biosphere model supporting the development of an Integrated System Model, with updated models, equations and site-specific data, described further in Section 14.2. The NWMO will continue to monitor developments in biosphere modelling in support of repository safety assessments.

The reference model and data as used in recent illustrative postclosure safety assessments are described in Gobien et al. (2018) and related references. This data will be supplemented by data acquired in the context of site characterization as well as technical programs designed to addess data gaps.

11.2 Terrestrial Environment

Ecological systems refer to the relationship between organisms and between those organisms and their environment. Characteristics of an ecological system include the ecosystem type, such as boreal and tundra, and natural cycles, such as seasonal variations, and random events, such as forest fires.

The postclosure safety assessment model (NWMO 2012) includes representations of forest, wetland, aquatic and agricultural features. Contaminants may migrate through these systems (e.g., via root uptake into vegetation) and subsequently be available in the food chain. The reference model ecosystem represents a constant temperate climate with conservative assumptions applied to assess the dose consequence to a small self-sufficient farming family.

Potential releases of contaminants from a deep geological repository are likely to impact the terrestrial environment initially through a groundwater pathway. The pathway into the terrestrial environment is primarily then through the water table and uptake by plants, through irrigation, or through natural groundwater release deposition or precipitation from the atmosphere (Section 11.4).

If a well is plausible, then this is likely the most important pathway for potential exposure of humans. Use of a well for irrigation also is an important path for distributing potentially contaminated groundwaters to soil, plants, and animals. Otherwise contaminants must reach surface through a shallow water table or other groundwater discharge locations.

The current biosphere model has simplified representations of soils and wetlands with optional irrigation from either groundwater (i.e. well) or a nearby surface water body, considered typically as sensitivity studies. These are modelled as time-independent entities with equilibrium transfer factors between the contaminated input water and any crop or forage products.

Based on the results of previous Canadian safety assessment case studies, the radionuclides most likely to reach the biosphere are relatively mobile, long-lived species, such as radioisotopes of iodine, chlorine, selenium and cesium. From 2002 to 2006, a series of literature reviews were conducted by NWMO in which the reference values for important biosphere transfer rates for these and other potentially important elements were assessed and updated (Sheppard et al. 2002, 2004a, 2004b, 2005a, 2005b). A three-year program from 2007 through 2009 conducted sampling to add further specific Canadian data. The sampling included farm animals and plants, fish and game animals. This work was summarized in Sheppard et al. (2012) and a series of journal articles (Sheppard et al. 2010a, 2010b, 2010c).

A literature review of background concentrations of radionuclides in surface waters and soils across Canada was completed in 2011, supplemented by environmental radioactivity measurements for the gaps identified in the literature (Sheppard et al. 2011 and Sheppard and Sanipelli, 2011). The review and measurements focused on primordial radionuclides, naturally occurring radionuclides of special interest to the NWMO program and fallout radionuclides.

Data described above are supplemented with data from CSA N288.1 (CSA 2014). However, it should be noted that some of the CSA N288.1 data are based on the references described above, and NWMO has made significant contributions to publically available data, most notably data for Iodine (Sheppard 2002).

Additional data will be linked with site characterization and environmental baseline programs. The NWMO will continue to monitor and review the literature.

With respect to overall biosphere processes, opportunities to test or validate the current models will be explored, both via the use of field data and through model and code comparisons. This can be accomplished through working groups such as BIOPROTA, looking at particular radionuclides.

11.3 Aquatic Environment

Aquatic freshwater systems (running waters, lakes) are generally adequately understood with respect to contaminant transport. However, modelling of the sediments is important. In many groundwater discharge areas, the radionuclides will pass through a sediment layer before reaching the waters. In other cases, the radionuclides may settle into sediment layers. In this way, the sediments may exercise a strong influence on radionuclide transport. In the short term, these processes will tend to reduce the outflow of radionuclides and result in lower doses. In the long term, however, radionuclides can accumulate in sediments, only to be released later due to draining of lakes and use of sediments as agricultural soils.

Past work on biosphere transfer factors described in the above section also included parameters relevant to aquatic freshwater systems, in particular fish transfer factors. As an example, the data on I-129 transfer in fish is illustrated in Figure 11-1. This generic Canadian work concluded in 2009, with the initiation of the NWMO siting program.

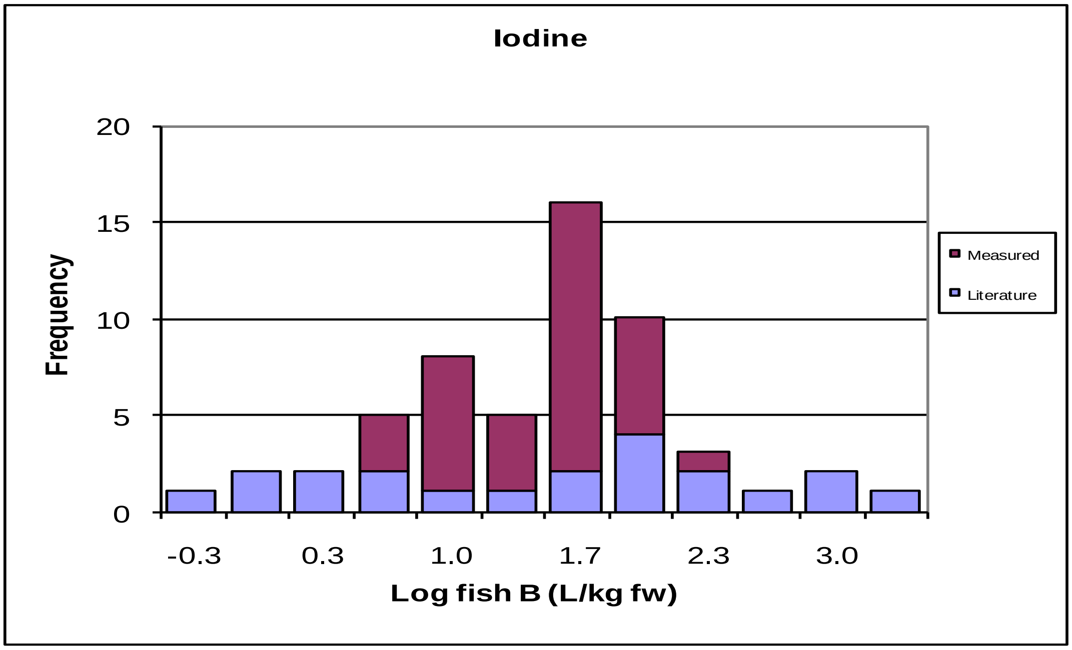

Figure 11-1: Iodine transfer factor data from the previous literature (blue) compared to additional transfer factors measured by Sheppard et al. (2012).

As none of the candidate sites are in a marine area, no work is planned on marine environments.

The NWMO is currently investigating transport models, primarily using HydroGeoSphere (Therrien et al. 2013), that have the ability to incorporate surface water features in some detail, and integrated with groundwater. This will provide a more regional scale perspective on transport, beyond the classical critical group.

Currently, information on aquatic environments used in postclosure safety assessment studies are taken from the CSA N288.1 Guideline (CSA 2014) and supplemented by data in Davis et al. (1993). Relevant data and their sources are summarized in Gobien et al. (2018).

Going forward, site specific information collected during site characterization will be incorporated into existing models. Literature review will also continue with a view to identifying information of interest to future modelling.

Similar to the terrestrial environment, opportunities to test or validate the current models will be explored, both via the use of field data and through model and code comparisons. This can be accomplished in part through working groups such as BIOPROTA, looking at particular radionuclides.

11.4 Atmosphere

Atmospheric transport processes and meteorology can also contribute to the physical transport of contaminans as gases, aerosols, or particulates. Many of the postulated preclosure safety assessment scenarios involve a fraction of the contaminants being suspended in the air and atmospheric contamination is the primary exposure pathway for humans during the preclosure period.

A critical process relevant to the concentration of contaminants in the atmosphere is atmospheric dispersion. In the preclosure assessments atmospheric dispersion is modelled using the Guassian dispersion model described in Canadian Standards Association (CSA) N288.2-M91. In current preclosure assessments, wet and dry deposition and plume depletion processes are conservatively neglected. Furthermore, atmosphere conditions during the preclosure period are conservatively assumed to be highly stable with low wind speeds and steady state meteorological conditions. In the future, the preclosure atmosphere model will be revised to include site specific meteorological and atmospheric data once available (climate change is discussed in the next sub-section).

Atmospheric transport pathways are typically of lower consequence (as compared to aquatic exposure pathways) during the postclosure period. In the postclosure assessments, contaminants released from a repository could potentially be volatile or become suspended by processes such as dust resuspension or irrigation spray. A simple dispersion model is used for postclosure assessments and is described in NWMO (2012). Other atmospheric data (e.g. dry deposition velocity, atmospheric dust load) adopted in illustrative postclosure safety assessment studies are taken primarily from the CSA N288.1 Guideline (CSA 2014) and supplemented by information Davis et al. (1993). Relevant data and their sources are summarized in Gobien et al. (2018). Going forward, atmospheric data collected in site characterization will be used to supplement and enhance existing data.

Some contaminants are volatile or have the potential for volatility in the surface environment. Of particular relevance is C-14 incorporated into carbon dioxide or methane, H-3 as water vapor, I-129 as iodine gas, Se-79 as selenium gas, and radon. The properties of relevant volatile elements (i.e., Ar, C, Cl, H, I, Kr, Rn, and Xe) have been the focus of past studies by AECL (Zach et al. 1996) and OPG (Sheppard et al. 2002, 2004a, 2005a, 2005b) to determine soil and surface water volatilization factors. Volatilization data for soils, surface water and fires are assessed to be well characterized and largely independent of site. Furthermore, illustrative postclosure safety assessments show that dose consequences from exposure to volatile elements are not significant relative to other pathways, such as eating contaminated foods or drinking contaminated water. The NWMO will continue its ongoing literature review in this area.

Meteorology is characterized by precipitation, temperature, pressure, wind speed and direction. These factors can influence repository siting, as well as contaminant movement through the biosphere. Meteorological data (e.g. wind speed, precipitation) adopted in recent illustrative postclosure safety assessments were taken from the Canadian Daily Climate Data (e.g., CDCD 2006) and supplemented with information in Davis et al. (1993).

Going forward, meteorological data collected during site characterization will be used to supplement and enhance existing data. Opportunities to test or validate the current models will be explored, both via the use of field data and through model and code comparisons. This can be accomplished in part through working groups such as BIOPROTA.

11.5 Long-Term Biosphere Evolution

Biospheres evolve significantly on relatively short time scales with respect to postclosure safety assessment time scales.

In the near-term, the main climate change of interest is global warming. This could affect the pattern of rainfall and seasonal temperatures, and therefore the surface water flows and specific ecosystems and has been the focus of joint international projects (e.g., Lindborg et al. 2018). Current work is underway at NWMO to develop a basis for assessing these near-term changes, which are relevant to the operations of the repository (Roberts et al. 2019).

In other countries like Sweden and Finland, with candidate sites on the coast, the shoreline displacement with time due to uplift is a critical factor in the biosphere. While post-glacial uplift is also occurring in Canada, the candidate sites are away from the coast and this is not a primary influence on the biosphere.

For Canada and for timescales of interest to repository safety, the most significant credible long-term variation is climate change leading to glaciation. Within the past one million years, much of Canada has been ice covered in a series of nine major ice ages. Each glacial cycle likely included several ice sheet advances and retreats through a given region. Current understanding of glacial cycles in Canada is discussed further detail in Section 10.1.

An ice age obviously causes large variations in the biosphere. The current temperate climate over much of southern/central/eastern Canada reflects interglacial conditions. However over the past one million years, much of the time the Canadian land surface was covered either with permafrost or an ice sheet. Thus the biosphere processes that are relevant now under temperate climate conditions may not be representative of conditions over most of the next one million years.

However, temperate climate based biosphere models are still very appropriate for repository safety assessment. Firstly, there is interest in the potential impacts in the near future (tens of thousands of years) where the climate is most likely to be temperate in southern/central/eastern Canada. Secondly, temperate climates are consistent with an agricultural lifestyle in which the impacts of a repository might be maximized through locally grown crops and domestic animals. In contrast, the cool climate conditions associated with permafrost are likely to have reduced crop yields and therefore lead to lifestyles which use resources from extended areas, which in turn result in lower potential impacts from any repository. That is, the self-sufficient temperate-climate farmer is a useful and generally conservative indicator of potential repository impacts. Illustrative Canadian safety assessments have therefore used a steady temperate climate assumption so that the long-term impacts of a repository could be reasonably gauged using a currently relevant and sensitive indicator.

NWMO has completed a glaciation scenario modelling exercise designed to improve quantitative assessment of the potential impacts of glaciations. In this case, a hypothetical repository was assumed on the Canadian Shield, and the effects of glaciations were modelled over a 1 million year period, including multiple ice ages. Contaminant transport within the geosphere was modelled in detail. The impact on humans was assessed by using a series of stylized biosphere states appropriate for each portion of the glacial cycle: temperate, permafrost, ice sheet and proglacial lake. The results show that a self-sufficient temperate-climate farmer using a well for water supply is a reasonable indicator of potential impacts, compared to other exposure groups that are relevant to the conditions occurring during much of a glacial cycle. This conclusion is consistent with other international studies (IAEA 2016; Walke et al. 2013; Avila et al. 2010). It may therefore not be necessary at the early site assessment stages to include detailed glacial cycle biosphere and dose models (Garisto et al. 2010; Walsh and Avis 2010; Chen et al. 2017).

Although no major concerns over dose impacts during permafrost periods have been identified, the recent modelling was based on limited tundra biosphere data. Opportunities to obtain further data on the main food chain pathways for humans under tundra conditions are of interest.

A further point of interest is the formation of permafrost and possibly stagnant zones where radionuclides may accumulate during extended periods, leading to a period after defrosting when exposures could be increased. NWMO has been improving its knowledge in this area, through participation in projects studying the edge of ice sheets (e.g. GAP, see Section 10, Claesson et al. 2016) as well as current participation in the CatchNet Permafrost Hydrology working group.

11.6 Human Behaviour

The diet and lifestyle characteristics of people living near the repository area determine their exposure pathways to any contaminant release.

During the preclosure period dose to the public in the vicinity of the repository surface facilities are considered. The preclosure safety assessment does not consider many lifestyle characteristics of the public in favour of conservatively assuming humans are present in the area with the highest atmospheric contamination to maximize exposure. The preclosure safety assessment considers the following exposure pathways:

- Inhalation;
- Immersion in air; and
- Groundshine.

Going forward, information from site characterization and detailed design of the surface facilities will be used to supplement the existing data. Preclosure safety assessment models will be evolved to consider additional exposure pathways (e.g., contaminated water pathways) as well as doses to workers. Literature review will continue with the objective of identifying additional data and maintaining awareness of international activities.

Illustrative postclosure safety assessments performed to date (e.g., NWMO 2018, NWMO 2017) assume diet and lifestyle characteristics consistent with those of a small self-sufficient farming household. The primary water source is a deep well, situated in the location that maximizes the capture of contaminants potentially released from the repository. Alternative diets and lifestyles have also been considered, notably in the glaciation scenario assessment of Garisto et al. (2010) which considers a hunter/gatherer and a postglacial fishing community. Data have also been developed for a representative aboriginal diet and lifestyle, but they will be updated to site specific information (Garisto et al. 2014).

The human dose exposure model used for the postclosure safety assessment accounts for a variety of potential internal and external exposure pathways, notably:

- Ingestion of drinking water;
- Ingestion of food;
- Ingestion of soil;
- Inhalation of air;
- Immersion in air and water; and
- External dose from groundshine and building materials.

For the postclosure safety assessment of impacts of non-radiological contaminants on humans is assessed by comparing the calculated media concentrations of hazardous elements against criteria (Section 14.2.2).

Data used in the assessment model are taken primarily from the CSA N288.1 Guideline (CSA 2014) and supplemented by information in Davis et al. (1993). Relevant data and their sources are summarized in Gobien et al. (2018).

Going forward, information from site characterization will be used to supplement the existing data, and literature review will continue with the objective of identifying additional data and maintaining awareness of international activities. Alternative lifestyle characteristics may also be developed through discussions with local people in the potential siting areas.

A different class of human behaviour are those actions that could directly impact the expected repository performance, notably inadvertent human intrusion. This is treated as a stylized scenario in the safety assessment.

11.7 Biota

Postclosure safety assessment studies estimate the potential significance of radiological and non-radiological repository releases on representative non-human biota.

For the assessment of impacts of radiological contaminants on biota, the partitioning behaviour of radionuclides between media and organisims is modelled using two different approaches. The first is the Concentration Ratio approach, which is based on equilibrium concentrations between media and organisms and is consistent with the ERICA model (Torudd 2010). The second is the Transfer Factors approach, which is based on the intake rate of food, soil, water and sediment for mammals and birds. The model considers the effects of radionuclides on a wide range of species that are representative of the main taxonomic groups found in three different simplified Canadian ecosystems (i.e., southern Canadian deciduous forest, boreal forest and inland tundra). A full description of the methods is provided in Medri and Bird (2015).

For the assessment of impacts of non-radiological contaminants on biota, the calculated media concentrations are compared against criteria that are relevant to biota.

The NWMO will continue to review the literature compilations of biota data and effects, for incorporation into safety assessment studies as appropriate. Canadian data, including tundra environments, would be of particular interest. International efforts to improve radiological assessment of biota will also be monitored, such as through further ICRP work (ICRP 2019). Participation in international working groups assessing the effect of repositories on non-human biota (e.g., BIOPROTA 2016) will also continue.

11.8 Research Program Summary

The preclosure safety assessment approach is partially illustrated in Liberda and Leung (2018). Contamination of the atmosphere is the primary exposure pathway during the preclosure time period. The atmosphere model and data are consistent with the standardized information in the CSA N288.2-M91 Guideline (CSA 2003).

The postclosure biosphere safety assessment model is described in NWMO (2012). Many of the transport pathways and associated data needs are based on standardized information in the CSA N288.1 Guideline (CSA 2014) and supplemented as required by information in Davis et al. (1993).

Site Selection and Characterization Phase

During this phase, existing biosphere data will be supplemented by site specific data collected in the site characterization activities. The main modelling improvement will be the incorporation of surface waters into the overall water flow and contaminant transport modelling (e.g. using HydroGeoSphere).

Site characterization will also provide additional information on local interest and habits that will contribute to the range of potential exposure groups in future site-specific assessments.

Ongoing literature review and participation in international programs (such as BIOPROTA) will continue, with the objective of ensuring the existing biosphere modelling approach remains appropriate and conservative. Improvements and adaptions will be implemented if warranted.

Site Preparation and Construction Phase

During this phase, additional field studies or sampling campaigns will be established as needed to resolve important uncertainties ideintified during prior work.

Operations, Monitoring and Closure Phase

During the operations, monitoring and closure phase it is expected that biosphere data and conceptual models will be well established. During operations however, ongoing literature review and participation in international programs will continue, with the objective of ensuring the biosphere modelling approach remains appropriate and conservative. Improvements and adaptions will be implemented if warranted. Confirmatory or follow up studies may take place during this time as apprropriate.

Major Facilities

No major facilities are required for furthering the study of safety specific site data and improving the biosphere model. It is expected that facilities currently available at universities and contractors will continue to remain available.

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12 MONITORING

The implementation of APM will require a variety of monitoring activities, including environmental, community, operational safety, safeguards and facility performance (IAEA 2014). This monitoring will support the design, site investigations, safety case and regulatory approvals. An overall framework for monitoring of a Canadian deep geological repository is given in Simmons (2006). Recent perspectives on monitoring are provided in the European MoDeRn project (Solente 2013, also www.modern2020.eu) and the monitoring reports at Olkiluoto, Finland (Posiva 2012) and Forsmark, Sweden (Berglund and Lindborg 2017).

12.1 Environmental Monitoring

Environmental monitoring of the near-surface physical and biological characteristics of a candidate site is initiated with field work, for example as part of permissions for borehole drilling. It will expand with the site characterization activities at the preferred site to support the initial approval of the project. It will then develop into a mature program that supports the operation of the facility (i.e. confirms that it meets the design and licensing basis), and eventually its closure.

Environmental monitoring is standard practice at all nuclear facilities including uranium mines (e.g. CSA 2015; CNSC 2017). A description of current technologies for environmental monitoring around a repository site is provided in Posiva (2012) and Berglund and Lindborg (2017). No specific research is planned into environmental monitoring technologies, although NWMO will maintain awareness of developments in technologies that may improve our ability to monitor. An example of this is a current activity to consider new technologies for monitoring bats.

12.2 Community Monitoring

Communities may be monitored as part of assessing socio/economic or health effects of the project on nearby communities. A simple example would be census data, which is provided by Statistics Canada but could be analyzed in the context of assessing community impacts as part of the approvals basis. Major industrial projects within Canada, including uranium mines, provide background on available methodologies. No specific research is planned into community monitoring technologies.

12.3 Occupational Health and Safety Monitoring

An Occupational Health and Safety Program would be implemented for all periods in the lifecycle of a repository when there are workers involved (CSA 2014). As the project would be a large industrial undertaking with significant underground construction and operation, as well as the handling of used nuclear fuel, there would be significant industrial and radiological components to the occupational health and safety program. The methods of monitoring occupational health and safety from an industrial and radiological perspective are well-established. No specific research is planned into occupational health and safety monitoring.

12.4 Safeguards

Safeguards monitoring is discussed in Section 13.2.

12.5 Repository Performance Monitoring

The objectives of performance monitoring in a deep geological repository are to:

- confirm that the various repository components are placed and operating according to their design requirements and intended purpose; and
- build confidence in the understanding of the physical and chemical processes that are important to the performance of the repository.

Performance monitoring would include complementary approaches, including (Simmons 2006):

- laboratory tests and surface demonstration tests;
- tests and demonstrations in generic underground research laboratories;
- demonstration tests in a underground demonstration facility at the site of the deep geological repository; and
- *in situ* monitoring of the repository systems.

The mix of these different approaches will vary with the repository development stage as discussed further below.

12.5.1 Site Selection and Site Characterization Phase

During the site selection and characterization phase, monitoring would be in the context of developing baseline information on the site, from geological conditions to surface conditions. This would be described in the Site Characterization Plan.

A potential research area is in developing capabilities to monitor the repository performance, such that these were available for the construction and operation phase. Martino et al. (2001) summarized the state-of-knowledge on instrumentation systems for monitoring engineered seal systems in the context of Canadian experimental studies. Based on this and other work, a general observation was the need for instruments that would operate for sufficient length of time under the combination of hydraulic pressure (up to 10 MPa), temperature (80-100ºC) and salinity (> 90 g/L).

The NWMO plans to stay informed on monitoring capabilities through its involvement in research projects at underground research laboratories (URLs) around the world, including those listed in Table 2-1.

12.5.2 Site Preparation and Construction Phase

An extensive geological verification program would be carried out in concert with the construction of the repository, including the initial shaft excavation and establishment of the central services area. These will verify that the geological characteristics previously determined through surface based measurements are confirmed in the underground. An example of this type of program is the Geoscientific Verification Plan developed in support of OPG's proposed Low and Intermediate Level Waste (L&ILW) DGR (NWMO 2014).

The geoscientific verification plan for the APM repository has not yet been developed, but is likely to include the parameters listed in Table 12-1 (geotechnical) and Table 12-2 (geoscience).

Table 12-1: Key Geotechnical Parameters and Potential Monitoring during Construction

Geotechnical Parameter	Potential Monitoring Activities during Shaft Sinking	Potential Monitoring Activities during Lateral Development
Rock Mass Quality	Geological mapping of shaft excavation wall, e.g. visual, photographic, LIDAR.	Geological mapping of tunnel and room excavation surfaces, e.g. visual, photographic, LIDAR.
Groundwater Inflow	Probe hole drilling in advance. Observation of seepage.	Probe hole drilling in advance. Observation of seepage.
Excavation Deformation	Array of extensometers along shaft. Inclinometer system on shaft liner.	Array of extensometers in tunnels and rooms. Analysis of consecutive LIDAR surveys. Visual inspection.
Rock Loading	Pressure cells in rock liner and/or at liner/rock interface. Stress cells on liner surface.	Stress cells embedded in roof rock.
Geomechanical Properties	Up-scaling tests using larger blocks from underground.	Up-scaling tests using larger blocks from underground.
In situ Stress	In-situ stress measurement at repository horizon.	In-situ stress measurement.
Rock Pillar Integrity and Response	Not applicable.	Seismic tomography. Horizontal borehole investigation within pillars. Analysis of extensometer, stress cell and LIDAR data.

Table 12-2: Key Geoscience Parameters and Potential Monitoring during Construction

Geoscience Parameter	Potential Monitoring Activities during Shaft Sinking	Potential Monitoring Activities during Lateral Development
Seismicity	Regional and local seismic monitoring network	Regional and local seismic monitoring network
Rock Mass Quality	As in Table 12-1. Mapping includes geological features that could enhance radionuclide migration.	As in Table 12-1. Mapping includes geological features that could enhance radionuclide migration.
Excavation Damage Zone	Point investigations of EDZ along shaft wall.	Point investigations of EDZ along tunnel and rooms. E.g. ultrasonic velocity measurement, coring rock for inspection, packer testing over small intervals, ground penetrating radar.
Fracture Infill	Collect/analyze samples for mineral chemistry, fluid inclusions, dating.	Collect/analyze samples for mineral chemistry, fluid inclusions, dating.
Groundwater Chemistry	Collect/analyze groundwater chemistry from seepage/fractures.	Collect/analyze groundwater chemistry from seepage/fractures.
Two-phase Flow	Not applicable.	Rock core samples for multi-phase transport property measurement.
Diffusion / Transport Properties	Not applicable.	Rock core samples for diffusivity and sorption property measurement.
Microbiology	Not applicable.	Sampling and in-situ studies of microbial activity.

These parameters can be measured using the techniques currently available such as described in NWMO (2014). No specific research on monitoring technologies is planned, although NWMO will continue to participate in projects at URLs which may include testing or development of advanced techniques, and may sponsor the development and testing of specific novel technologies on a case-by-case basis.

12.5.3 Operations, Monitoring and Closure Phase

In addition to environmental and other monitoring already described above (Section 12.1-12.4), monitoring of repository performance during the operations, extended monitoring and closure phase would include the following general categories:

- Continued geological monitoring;
- Continued Underground Demonstration Facility (UDF) tests; and
- Specialty borehole tests and monitoring.

The first category would include periodic checking of the geological information noted above, in particular to detect any significant changes. The monitoring would be primarily concerned with measuring the physical conditions in the host rock and changes in those conditions including:

- In-situ stress fields in the rock mass, and changes caused by excavation and heating;
- Groundwater pressure and chemistry, and changes caused by excavation and heating;
- Initiation, propagation and dilation of fractures, deformation or displacement of rock around openings, and changes in EDZ; and
- Rock temperature, and changes caused by excavation, ventilation and heating.

The second category would include dedicated tests conducted within the UDF (or other niche areas). As noted in Section 2.4, there will likely be two main areas. The first is the early UDF area where tests are installed soon after repository excavation has connected two shafts to allow an air flow and underground working area to be established. The second is a larger area for trial emplacement room tests. Tests that could occur here include:

- Rock mass properties;
- Excavation method optimization to minimize EDZ;
- Initiate material tests;
- Initiate sealing system tests;
- Full scale excavation/placement tests for optimization and worker training, probably with non-nuclear containers;
- Pilot instrumented emplacement room (with dummy containers or real containers); and
- Retrieval demonstration test.

In the demonstration tests, containers could be installed in a well-monitored environment similar to a repository emplacement, monitored continuously and decommissioned for examination at various times. If containers with used fuel are used, and if they are installed with close-by monitoring, there may be an expectation that they would be retrieved and re-emplaced without the monitoring hardware as part of the final repository operations activities.

The third category of monitoring covers specialty tests that may occur across the repository and check aspects of performance of the as-emplaced containers (e.g. Villagran 2012). Important factors in planning for this monitoring are the longevity of the sensors and whether they could affect the long-term stability of the system that they are monitoring. For example, large scale experiments to date have embedded pressure, humidity or other active sensors within buffer elements, and have often observed that the power or signal cables can affect the test as they penetrate through the otherwise self-sealing clay buffer. Also, many of these instruments have a lifetime measured in years under in-situ conditions, which is short relative to the potential time frame of interest. Together, this puts an emphasis on monitoring that is remote, such that the instruments can be maintained if necessary and such that they do not interfere with the carefully controlled conditions in the engineered barriers.

These constraints generally limit the testing to that conducted through boreholes around an emplacement room, with enough standoff distance to minimize risk of interference with the rooms, and to remote sensors such as acoustic emission monitoring.

The performance and longevity of many monitoring instruments was and is being tested in underground research facilities (e.g. see Table 2-1) (e.g. Martino 2001; Dixon et al. 2002).

One area that NWMO will maintain awareness is the development of wireless sensors, which avoids concerns over cabling. Current research indicates that high frequency signals at 169 MHz can be transmitted about 3.5 m in clay-based rock and over 5 m in saturated bentonite (Solente 2013). Alternatively, less data can be transmitted farther (e.g. over 200 m) using low frequency methods at around 1.5 kHz, with lower power needs (Solente 2013).

12.6 Postclosure Monitoring

Monitoring will also continue after the repository has been closed (IAEA 2014). Postclosure monitoring will include environmental monitoring of surface and shallow groundwaters. This will monitor the evolution of the site from the repository operations state to the postclosure state, as well as verify that the repository is not posing any immediate risk.

Further monitoring that could be undertaken would focus on parameters that are indicative of the conditions near or within the repository. Thompson (2003) provided an outline of a potential monitoring program. Options include monitoring through deep boreholes in the vicinity of the repository (e.g. groundwater chemistry, radionuclides, pressure, temperature), remote sensing such as acoustic emission or microseismics arrays from surface or near-surface, and satellite monitoring of surface temperature and elevation change.

As part of the closure of the repository, the specific nature of ongoing monitoring will be decided at that time (100+ years in the future) based in part on the technologies then available, and informed by experience with monitoring during earlier phases of the repository.

12.7 Knowledge Preservation

A related aspect to monitoring the repository, is preserving information on the repository over the long timescales required to, in part, prevent inadvertent intrusion, but also to keep future generations informed to support their planning and decisions.

The NEA Radioactive Waste Management Committee initiative on the Preservation of Records, Knowledge and Memory across Generations, the RK&M project (NEA 2018) reviewed the available information and proposed some directions on this topic. Some of the conclusions were that a variety of approaches should be used to ensure transfer. On a technical note, the concept of key information files was proposed that would establish minimum information about a given repository that would be preserved widely and in various formats. In the Canadian context, this key information file would be discussed with Archives Canada in terms of format and distribution.

As a specific technical example, NWMO is maintaining its own inventory of the used fuel generated to date, as described in Section 3.

12.8 Research Program Summary

Monitoring plans will be developed in parallel with NWMO's program phases. These plans will include the identification of the parameters to be monitored and the technologies to be used. They will be supported by the technical research program in part through NWMO knowledge of technologies gained through its participation in international research projects.

Recent reviews of the state-of-science in repository performance monitoring technologies were provided by the EU MoDeRn project (Solente 2013) and the monitoring report at Forsmark, Sweden (Berglund and Lindborg 2017).

<u>Site Selection and Site Characterization Phase</u>

Monitoring will start during this phase in the candidate siting areas. At the Ignace-Wabigoon site, hydraulic head instruments are already in place in the first deep borehole, and baseline environmental monitoring, a meteorological station and local microseismic array are in planning.

NWMO is not planning on a targeted instrument technology development program. We will work with available technologies and apply or convert them as appropriate to our circumstances. A key driver for this in the near term is our involvement in international projects, where state-of-art instrumentation is often used or tested. NWMO's participation in these projects is in part to gather experience in the capabilities and limitations of the instruments, and in scientific projects addressing the issues.

<u>Site Preparation and Construction Phase</u>

Monitoring of the environmental, geotechnical and geoscientific conditions during the shaft excavation and initial lateral excavation at the emplacement level will be important to confirm expectations from prior surface based measurements. This can be conducted using currently available methods.

In situ tests on engineered barrier and repository operation topics will be conducted in the UDF, which would be constructed early in the lateral excavation stage of construction. This will include both short term tests that would inform the Operating Licence application, as well as installation of longer-term tests that could be used to inform future closure decisions, such as installing sealing material compatibility tests in boreholes, or excavation and non-nuclear container placement in a trial emplacement room. Monitoring equipment would be installed as part of these tests, using available technologies.

Operations, Monitoring and Closure Phase

Monitoring of the environmental and geological conditions would continue, as well as long-term tests within the UDF. Remote monitoring (e.g acoustic emission monitoring), tunnel monitoring (e.g. groundwater chemistry, temperature) and borehole monitoring (e.g. chemistry, radioactivity, porewater pressure, temperature) would also be used, to verify that at least at distances of tens of meters from the containers, that conditions are as expected.

Plans for monitoring methods to support the postclosure phase would be updated during this period, including any development needs, in order to support the closure decision and initiate the postclosure monitoring program.

Major Facilities

The major facility for monitoring will be the UDF, constructed at the repository horizon at the DGR site.

12.9 References

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13 CRITICALITY AND SAFEGUARDS

13.1 Criticality

Nuclear criticality requires a sufficient concentration and critical mass of fissile isotopes, the presence of moderators in a favorable geometry and the lack of neutron absorbers.

Due to its lack of enrichment, criticality of standard CANDU fuel cannot be achieved outside of a nuclear reactor where it is maintained in a defined configuration surrounded by heavy water coolant and heavy water moderator. A criticality assessment confirmed that there is no credible risk of criticality for the used CANDU fuel emplaced in the repository using the current container configuration (Garisto et al. 2014).

These criticality calculations were conducted using well established codes, such as the MCNP code (LANL 2017). The cross-sections and neutron data used by the code are from established international datafiles, such as ENDF/B library (Brown et al. 2018; Chadwick et al. 2011). There is ongoing international work to continue to improve the supporting information, such as nuclear cross-sections and decay data (Ilas et al. 2012; Francis et al. 2014; Gauld et al. 2014). NWMO does not intend to carry out research in this area beyond that needed to ensure its criticality calculations needed for design and licensing support are complete and up-to-date.

Criticality assessments will be required for the non-CANDU fuels, specifically for any fuels enriched in fissile isotopes,and to consider low probability events. Such fuels would include the non-standard research fuels and fuel materials from AECL, and could include other fuels such as those resulting from potential Small Modular Reactors. Scoping calculations are planned in the near-term to understand the implications, and complete assessments consistent with CNSC (2018a) would be carried out to support design and licensing support. Additional guidance from international standards (e.g., ISO 2018) and relevant reports published by internal working groups, such as the NEA Working Party on Nuclear Criticality Safety, would be considered for the calculations, as applicable. It is presently not expected that additional criticality research will be needed.

13.2 Safeguards

Safeguards, as described in the Statute of the International Atomic Energy Agency (IAEA), are measures used to ensure that “special fissionable and other materials, services, equipment, facilities, and information made available by the Agency or at its request or under its supervision or control are not used in such a way as to further any military purpose” (IAEA 1956; 1989).

Nuclear material is defined by the IAEA as any source material or special fissionable material. Source material is, among other things, uranium containing the mixture of isotopes occurring in nature. Special fissionable material is Pu-239, U-233, uranium enriched in the isotopes 235 or 233, or material containing any of these radionuclides. “Significant quantities” are defined in Table II of IAEA (2002), and include 8 kg of Pu (at <80% Pu-238), 8 kg of U-233 and 25 kg of U-235 (at >20% U-235).

The used nuclear fuel at the APM facility would be subject to nuclear material safeguards. Canada, as a signatory of the Nuclear Non-Proliferation Treaty (NPT), has concluded a safeguards agreement with the IAEA (1972; 2000). Under the terms of this agreement, Canada has concluded individual safeguards agreements for each of its existing nuclear facilities and is obligated to reach similar agreements for future nuclear facilities. It is anticipated that, when the APM facility is in the design stages, the IAEA and Canada will conclude an agreement covering the DGR and associated surface facilities. The safeguards approach would be developed and implemented by the IAEA, in consultation with the CNSC, and the NWMO as facility operator.

Most safeguards activities at the APM facility will focus on addressing two of the IAEA's main objectives, that is to detect any diversion of the declared nuclear material, and to detect any undeclared production or processing of nuclear material. Guidance with respect to the safeguards measures for long-term management of used fuel, including geological disposal, is provided in IAEA's documents NW-T-1.21 (IAEA 2010) and NF-T-3.1 (IAEA 2018a). Implementation of IAEA's safeguards approach will have specific emphases during the construction phase, operation phase, and postclosure of the DGR. In particular, during construction, the emphasis will be verification of design information; this activity will then continue throughout the life cycle of the facility, until its closure. During operation and prior to the closure of the repository, the emphasis will be on verification of material inventories and flow. During postclosure, the emphasis will be on verification of no changes at the site.

Verification of design information by the IAEA during construction is intended to confirm that the construction is consistent with the declared design of the repository including the surface and underground facilities and the facility equipment, and to detect any possible undeclared activities that would make the safeguards measures less effective (IAEA 2011). The safety-by-design concept (Bjornard et al. 2010) will be considered to ensure that nuclear safeguards providisions and features are included in the APM facility early stages of the detailed design.

During operation, the IAEA's approach is based primarily on confirmation of the identity and integrity of items, i.e. used fuel bundles, until they are sealed within used fuel containers, and then the used fuel containers after that; and maintenance of continuity-of-knowledge of these items by containment/surveillance. Typical equipment that may be used for safeguards verification and monitoring is described in IAEA (2011).

CANDU fuel bundles are typically identified by serial numbers, and in principle traceable to their specific irradiation history and traceable to specific storage modules. However it is expected that the UFPP will require a method to validate some heat generation / radiation field related characteristics of each fuel package as individual bundle or as a single UFC. This characteristic would likely include something related to fissile content, and therefore also provide information from a safeguards perspective. This may require some method development.

After placement in container, continuity of knowledge of the used fuel can be achieved through implementation of an identification system for each container in the UFPP and the repository, and implementing robust containment and surveillance measures. A review by Clementi et al. (2018a, 2018b) of the existing tagging technologies included radio frequency identification (RFID), reflective particle tags, reflective laser scanning, ultrasonic systems and other concepts. The review concluded that the ultrasonic system would meet most of the requirements for copper canisters identification and authentication. SKB has initiated a project with the European Commission Joint Research Centre, looking to develop a technique to tag the identity of the canister on the inside such that it can be identified from the outside with the aid of ultrasonic testing, with no impact on the integrity of the canister (SKB 2016).

Alternative methods could be considered depending on the availability of the technology; ideas include use of the Passive Neutron Albedo Reactivity technique (Tobin et al. 2018a,b), developing a fingerprint for each UFC weld (Mongiello et al. 2013), radioisotope tagging (Chernikova and Axell 2014), direct measurement of the UFC content using neutrons (Conlin and Tobin 2011), or using emerging muon detection and imaging technologies (Jonkmans 2014).

Maintaining an accurate accounting of the nuclear material inventory in the UFPP and the repository is another key aspect of the safeguards. A near real-time nuclear material accounting system will need to be developed (CNSC 2018b).

During the postclosure phase, IAEA safeguards may include inspection and monitoring to verify that there are no changes at site, i.e., to confirm the lack of nuclear material or activities above ground at the site, as once the repository has been sealed, physical inspection of the emplaced containers will not be possible. The monitoring and the nature of any ongoing technical research will need to be assessed closer to this time (see Section 2.4.4). Safeguards for the used fuel disposed of in the DGR would be maintained as long as the appliable safeguards agreement remains in force (IAEA 2018a).

13.3 Research Program Summary

The criticality and safeguards information supports the development of the design of the repository. Criticality assessments also support the safety assessment.

Site Selection and Site Characterization Phase

During this phase, criticality assessments for non-CANDU fuels enriched in fissile isotopes will need to be performed. Current work is underway to obtain the relevant input data from CNL on the non-CANDU used fuel. Criticality scoping calculations are currently planned for non-standard and enriched Canadian nuclear fuel. Similar assessment would be needed for SMR fuels if such reactors are implemented.

A conceptual Safeguards Plan will be prepared, describing the elements of the system-by-design approach to be implemented, the system to be in place for nuclear material accounting and verification, technologies to be used for keeping the continuity of knowledge of the used fuel up to the final emplacement in the repository, and monitoring measures to be in place following closure of the repository. This conceptual plan may identify technologies that need development in support of the DGR.

The development of an independent method to identify and authenticate the content of a fuel bundle or the UFC needs to be done during this phase. In the first stage, this would involve literature review, and monitoring the developments internationally (e.g., IAEA 2018b, SKB 2016).

Site Preparation and Construction Phase

Further work may be needed to refine the nuclear material accounting system to meet the IAEA and CNSC safeguards requirements. A Safeguards Plan will be prepared, to describe the nuclear material accounting methodology to be used during the operation, monitoring and closure of the repository.

Advancements in the safeguards technologies will continue to be monitored. The development of the method to identify and authenticate the content of a fuel bundle or the UFC will also continue during this phase.

Operations, Monitoring and Closure Phase

The primary safeguards activity will be tracking and reporting the inventory in accordance with IAEA and CNSC safeguards requirements.

Major Facilities

No major new research facilities are required. It is expected that facilities currently available at universities and other Canadian and international research laboratories will continue to remain available. During the site preparation and construction phase, the Underground Demonstration Facility could be used to demonstrate the the implementation of safeguards monitoring measures during the operations, extended monitoring and closure of the repository.

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14 SAFETY ASSESSMENT

Safety assessment evaluates the operational or preclosure safety, and the long-term or postclosure safety, of the facilities for long-term management of used nuclear fuel, and in particular for a deep geological repository. It includes the assessment of potential impacts on workers, the public and non-human biota, from both radioactive and chemical hazards in the used fuel. This is separate from conventional industrial health and safety, which is part of the design and operations of the facility.

Prior to site selection, safety assessment case studies have been conducted on conceptual designs in hypothetical sites in order to understand the key factors relevant for safety, and to develop the approaches to safety assessment for a candidate site.

14.1 Preclosure Safety

The preclosure period includes site preparation, construction, operation, decommissioning, monitoring and closure. Topics include normal operations safety (public and worker dose), and malfunctions and accidents.

In the context of a geological repository and related facilities for used fuel, these topics were addressed as part of AECL's Environmental Impact Statement (AECL 1994, OHN 1994), and reviewed as part of the NWMO options study (NWMO 2005). In 2014, a preliminary dose assessment of the facility was carried out to guide ALARA (As Low As Reasonable Achievable) development of the repository concepts (Reijonen et al. 2014), and a preliminary hazard identification study was conducted for the Mark II conceptual design (Reijonen et al. 2016, Liberda et al. 2017). Internal and external initiating events were considered; accident scenarios were identified and grouped based on anticipated initiating event frequencies. In 2017, preliminary radiological public dose calculations were carried out for the identified accident scenarios (Liberda and Leung 2018). These studies were based on a generic site.

The preclosure safety assessment will be updated in parallel with the ongoing work to develop more detailed plans for operations and surface facilities. The current conceptual design is planned to be updated in 2019.

Methods to conduct preclosure safety assessment are expected to be sufficiently similar to existing methods for nuclear facilities that no specific method research is planned. Any software will be developed and verified per nuclear software quality assurance requirements.

Potential research topics relevant to preclosure safety are:

- Waste characterization;
- Criticality;
- Abnormal events and accidents;
- Behaviour of used fuel / packages under normal and accident conditions;
- Site-specific properties for safety assessment.

Waste characterization is addressed in Section 3. Criticality is discussed in Section 13. The other topics are addressed below.

14.1.1 Abnormal Events and Accidents

A preliminary study was carried out to identify potential internal accident scenarios that may arise during the operations phase for the repository, based on a conceptual design of the used fuel packing plant and repository (Reijonen et al. 2016). In this preliminary study, a failure modes and effects analysis (FMEA) was used to identify potential 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 initiating event frequencies were obtained based on data from the nuclear industry and from earlier used fuel management studies (AECL 1994).

In general, as the fuel is solid and does not require active cooling, and is minimally handled outside of containers, there are few internal accidents of potential significance. However the number of fuel bundles handled is large, so events with low frequency may still be relevant. NWMO will continue to monitor the literature to improve frequency estimates for key initiating events, including nuclear, mining and chemical industry experience, and update its assessment as the design evolves.

The potential external events are dependent on the site. As part of the site characterization phase, the external events will be evaluated. Two specific important external events are seismicity and flooding.

Research related to the seismic hazard potential is described in Section 10.3. The potential impact of climate change on flood risk also needs to be considered given the operating timeframe for the repository. In the near term, work is planned to review the climate change impacts on precipitation and update the estimates of the flood potential for the regional areas under consideration as potential siting areas. It is expected that this forecast would be periodically updated in the future as part of the safety assessment / licensing review.

14.1.2 Site-Specific Properties for Safety Assessment

Preclosure safety assessment employs an environmental transfer model to calculate potential dose to the public from the airborne and aqueous releases from a nuclear facility under normal and accident conditions. Canadian Standards Association (CSA) provides guidelines for the model calculations (CSA 2003, 2008 and 2014). CSA (2008) also provides regional default values for some parameters for southern Ontario, western Ontario, eastern Ontario, Quebec and Maritimes.

Depending on the site location, additional site-specific data may be needed, and integrated with regional or other relevant data. This site specific data would be acquired in the context of site characterization, e.g. installation of a meteorology tower.

A site specific survey will be needed for the DGR site to support the licensing application. This survey may include:

- Population distribution (e.g. family size, distance from facility);
- Land use (e.g., residential, farm, commercial, forestry, hunting);
- Source of water for drinking, bathing, farming (e.g., private well, lake water); and
- Food obtained from local sources (e.g. gardens, hunting, wild plants).

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

A key aspect of the preclosure safety assessment is the behaviour of the used fuel and packages under normal and accident conditions.

CANDU fuel is a solid waste form, non-volatile and contained within Zircaloy sheathing. Oxide layer formed on the endplate during in-reactor service are thin and adherent (Mirilovic 2019). Under normal handling conditions, there should be no appreciable radioactivity releases from the fuel. The gamma and neutron fields, and thermal output, would be known from the waste characterization described earlier.

However, some fuel may be damaged during transport to the DGR, or during handling within the Used Fuel Packaging Plant. These could result in some release of particulate or volatile elements from the used fuel. These releases would be handled within the surface facilities as part of the design basis (e.g. particulates captured on a High Efficiency Particulate Air (HEPA) filter system). Experience with loading of CANDU used fuel into dry storage containers or baskets, and the subsequent handling of these baskets including drying, helium backfilling, transport and seal welding has not indicated any significant issues with respect to releases (Roman and Khan, 2006). However the fuel handled at the DGR will be older fuel. The integrity of older fuel that would be received at the DGR is discussed in Section 4.1. From a preclosure safety assessment perspective, uncertainties in fuel integrity will be handled by conservative assumptions. The NWMO is planning on undertaking a normal operations assessment in the 2019-2020 timeframe. The NWMO will also look for opportunities to learn from others' used fuel handling experience (e.g., U.S. INL 2005, participation in the NEA Expert Group on Operational Safety).

A preliminary hazard identification found drop (impact) and fire with waste packages as potential accident scenarios to consider (Reijonen et al. 2016). The sealed used fuel container (UFC) and the used fuel transportation package (UFTP) are designed to withstand relevant drops or fires without compromising their containment function, so are not themselves the primary risk. These capabilities will be tested through modelling and field tests as part of their engineering design and (for UFTP) certification.

Of interest from a preclosure safety assessment perspective are cases where the fuel is not yet sealed in a container, or the container itself is not fully closed. In order to estimate the radiological release source term in these accidents, the preliminary assessment (Liberda and Leung 2018) followed the U.S. Department of Energy (DOE)'s five factor formula - material at risk, damage ratio, airborne release fraction, respirable fraction, and leakpath factor. The assigned values for the five factors in that study were based mostly on the U.S. DOE Handbook (U.S. DOE 1994) and the subsequent U.S. DOE standard (U.S. DOE 2007), as well as values used in the Yucca Mountain assessment (U.S. DOE 2009). These source term values were considered overall conservative, taking into account in part differences in used fuel characteristics, container and handling requirements (e.g. the lower burnup of CANDU bundles). Also recent data from a CANDU bundle irradiated end plate confirms that the surface layer was strongly bound, and therefore the surface material would not be readily released in an accident (Mirilovic 2019).

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

14.2 Postclosure Safety

The postclosure safety assessment forms part of the overall safety case, which itself is the integration of arguments and evidence that describe, quantify and substantiate the safety, and the level of confidence in the safety, of the deep geological repository and associated facilities.

The postclosure safety assessment uses as input many of the research and development activities described in this report, together with additional information obtained from the site characterization and the engineering proof test activities. Postclosure safety research and development work focusses on topic areas important to the safety assessment that would not normally be part of these other programs. These topic areas are listed and discussed below:

- Safety Assessment methods (including computer codes);
- Acceptance Criteria (used to judge the acceptability of safety assessment results); and
- Natural Analogues.

14.2.1 Postclosure Safety Assessment Methods

Postclosure safety assessments are designed to align with the expectations of CNSC Regulatory Document REGDOC-2.11.1, Volume III: Assessing the Long-Term Safety of Radioactive Waste Management (CNSC 2018). Additional international guidance applicable to the safety assessment are considered, as applicable (IAEA 2011; 2012).

The NWMO has developed its postclosure assessment methodology through performing a series of illustrative postclosure safety assessments for conceptual repositories at hypothetical sites. The most recent iterations are NWMO (2018) for sedimentary rock and NWMO (2017) for crystalline rock, with earlier iterations described in Gierszewski et al. (2004), NWMO (2012), and NWMO (2013).

The NWMO is also a member of the NEA Integration Group for the Safety Case (IGSC), an international forum to share and discuss topics and approaches in safety case development. For example, the NWMO has participated in the NEA FEPs Database project, which is developing a reference list of Features Events and Processes to consider as part of structuring a safety case (NEA 2019). The NWMO also participates in the periodic Safety Case Symposia, where waste management organizations present their current safety cases.

In the future, the postclosure safety assessment will become more site focused, and the analysis methods will evolve consistent with site-specific information obtained from the site characterization. The NWMO will continue to participate in international activities related to the safety case to ensure that its methods are consistent with international best practice.

An important part of the safety assessment methodology is the selection and qualification of the computer codes used for safety assessment. A description of the main computer models currently in use, and references to supporting code documentation, can be found in the postclosure safety assessment documents (e.g., Section 7.4. of NWMO 2017, 2018). Two primary codes have been used for contaminant transport calculations in the current illustrative postclosure safety assessments, FRAC3DVS-OPG and SYVAC3-CC4.

- FRAC3DVS-OPG has been the reference groundwater flow and transport code. It is based on a commercial 3D finite-element / finite-difference code (Therrien et al. 2010).

FRAC3DVS-OPG supports both equivalent porous medium and dual porosity representations of the geologic media. Surface water transport however is not accounted for in this model. The NWMO intends to replace FRAC3DVS-OPG with Hydrogeosphere (Therrien et al. 2013). Hydrogeosphere (HGS) is the commercially available successor to FRAC3DVS-OPG; and incorporates a number of improvements including faster run time and the ability to integrate surface water transport.

- SYVAC3-CC4 has been the reference system model for estimating hypothetical dose consequences arising from the release, transport, decay, and biosphere transfer of radionuclides. The code implements a number of simplifications to enable rapid calculations, and can perform both deterministic and probabilistic calculations. The NWMO intends to replace this with a new model which incorporates more complex geometry and more accurate physical processes. Increased model complexity means increased run times; however, with the advances in computer speed and cloud computing, use of a more detailed model is becoming more practical.

Preliminary work is underway at NWMO to develop a combined model, the Integrated System Model (ISM). The concept is to use a series of linked models representing the near field, the geosphere and the biosphere, using commercially available computer codes. Thus, the ISM would combine a COMSOL based model for the container and near-field, HGS for the geosphere and surface transport, and an AMBER based model for the biosphere and for estimating doses. Given current technology, this combined system model is expected to be computationally tractible for deterministic simulations, and potentially for probabilistic analysis.

The development, verification and validation for each computer code is described in its associated Software Plan, consistent with NWMO technical computing software procedures, and with the CSA Standard N286.7-16 (CSA 2016). Code validation is an ongoing task, with further validation of specific process models or overall system-level code comparison performed when suitable opportunities arise. A summary of SYVAC3-CC4 verification and validation is available in Garisto and Gobien (2013) and similar validation summary document would be developed for the ISM in the future. The ISM submodels will also be calibrated against information available through the site characterization activities. Other more detailed supporting models would similarly be validated as discussed in other sections. For example, a detailed COMSOL-based model of THM processes important to near-field repository conditions is being developed and validated against a series of international experiments, described in Section 7.5 of this report. Other exercises include the gas transport model validation through participation in LASGIT, FORGE (Calder 2014), HG-A (Walsh et al. 2014) and currently through participation in GAST.

In the postclosure safety assessment itself, the different models are also compared with each other. For example, results from the system model are compared against equivalent results from the 3D transport model. These comparisons are described in the various postclosure safety assessment reports (e.g., Section 7.8.1.4 of NWMO 2017; 2018).

The NWMO will continue to develop improved models consistent with developments in software and in hardware, and increased knowledge from the supporting technical research programs described in other sections. Participation in international experiments and programs (such as GAST and DECOVALEX) will also continue with a view to improving understanding of repository behaviour and obtaining data for computer modelling and validation. Ultimately, site specific models will be compared with results from the site characterization work in order to enhance or confirm confidence in these models.

14.2.2 Acceptance Criteria

Acceptance criteria are used to judge the acceptability of safety assessment results. REGDOC-2.11.1 (CNSC 2018) identifies the following four categories be addressed in a postclosure safety assessment:

1. Radiological protection of persons;
2. Protection of persons from hazardous substances;
3. Radiological protection of the environment; and
4. Protection of the environment from hazardous substances.

For the radiological protection of persons, the NWMO relies on the substantive body of knowledge that is reviewed and summarized through the International Commission on Radiation Protection (ICRP) and reflected in international guidance (ICRP 2007; ICRP 2013; IAEA 2011) and Canadian regulatory documents.

Protection policies for non-human biota are not as mature as those for humans. Presently, NWMO uses a two-tiered approach that is based on the ICRP (2008) Derived Consideration Reference Level (DCRL) bands for biota, as well as the generic biota screening critieria proposed by ERICA (Garnier-Laplace et al. 2006) and PROTECT (Andersson et al. 2009), and the two-tiered approach outlined in Jackson et al. (2014).

For the protection of persons and the environment from hazardous substances, the NWMO relies on Canadian Federal and Provincial guidelines principally from the Canadian Council of Ministers of the Environment (CCME) and the Ontario Ministry of the Environment (MOE), supplemented as needed by internationally developed guidelines. NWMO has documented interim acceptance criteria from these sources in four environmental media: surface water, groundwater, soil, sediment and air (Medri 2015). These criteria are “interim” because they have not yet been accepted by the CNSC for use in licensing a deep geological repository.

These interim acceptance criteria do not exist for all elements in all environmental media. Accordingly, work was initiated in 2016 to perform a literature review with the aim of developing criteria for a key subset of missing elements. Based on this review, some work was initiated to further acquire data on Ru and Rh. An updated set of interim criteria resulted from this work has been published in Fernandes et al. (2019).

Further discussion of the proposed interim acceptance criteria can be found in the various illustrative postclosure safety assessments published to date, with the most recent being in Section 7.1 of NWMO (2018).

The NWMO will continue to monitor the literature and regulatory standards for updated information affecting the relevant criteria. NWMO will in particular update its dose conversion factors as updated values become available from ICRP. The proposed criteria will be discussed with the regulator at the appropriate point in the future licensing process.

14.2.3 Natural Analogues

Natural analogues are natural features (including materials) or processes that are similar to those in some part of the deep geological repository. They provide understanding or demonstration of how the repository may behave over time scales ranging up to many millions of years. Analogues exist for most components of the repository system including the used fuel, engineered and natural barriers, and for key processes such as contaminant transport (Milodowski et al. 2015).

In Canada, for example, the Cigar Lake uranium ore body is a significant natural analogue for the durability of uranium oxide, and the general containment ability of clay. This analogue was extensively studied by AECL and international partners in the 1990s. The NWMO has included qualitative discussions of this and other international natural analogues in the postclosure safety assessment reports (see, for example, Chapter 9 of NWMO 2017, and Chapter 10 of NWMO 2018), to build confidence in the long-term performance of repository components.

The NWMO is also a member of the Natural Analogue Working Group. The purpose of this group is to share knowledge on the use of natural analogues in supporting repository safety assessments. Currently, NWMO is considering opportunities to support further natural analogue work, possibly related to Cigar Lake uranium ore, or to the study of natural bentonite within the Tsukinuno mine in Japan.

Detailed investigations of in-situ natural systems will be conducted in the future as part of the site characterization work and presented in the site Geosynthesis report. The information about how the site has behaved in the past will be important in understanding how it will behave in the future. The NWMO will continue to monitor the literature and participate in relevant international natural analogues projects.

14.3 Research Program Summary

Safety assessments to date have been illustrative studies of conceptual designs at hypothetical sites. As the NWMO site assessment program is now considering specific siting areas, future safety assessment studies will be site-specific.

The safety assessment will use as input the results from the research and development activities described in this report, together with additional information to be obtained from the site characterization and from the engineering proof testing activities.

Siting and Site Characterization Phase

During this phase, information from site characterization and the engineering proof testing will be used to further evolve the assessment methodology, and a number of preliminary, iterative safety assessments will be performed prior to submitting a licence application for a specific site.

Ongoing literature review and participation in international programs will continue (such as NEA Integration Group for the Safety Case, and Expert Group on Operational Safety), as well as possible opportunities to learn from the experience of other Waste Management Organizations (e.g., ANDRA, Nagra, Posiva, SKB) with the objective of ensuring the modelling approach remains appropriate and consistent with international best practice.

Work to improve the detailed modelling of system behaviour through development of combined-code platforms will continue.

Confidence in computer models will improve as modelling work continues, building on results of international projects such as DECOVALEX and the Mont Terri FE experiment, and through scale-model experiments to be conducted in Canada. Additional modelling exercises will be performed as appropriate opportunities arise.

The NWMO will continue to participate in experiments or studies that will improve confidence in the modelling of the repository, including possibly natural analogues.

<u>Site Preparation and Construction Phase</u>

During this phase, it is anticipated that the safety assessment will be mature; however, excavation of the shaft, access tunnels and placement rooms may result in changes to the understanding and parameterization of the geosphere and the associated updated engineering designs that must be accounted for in a revision to the safety case.

The NWMO will also maintain participation in international projects pertinent to supporting the safety case and continue to incorporate/learn from the relevant experience of other Waste Management Organizations.

<u>Operations, Monitoring and Closure Phase</u>

Practical experience from the operation of the facility, as well as from other national facilities likely to operate in this timeframe, will be used to verify and improve the information and models in the safety assessment. The NWMO will also maintain participation in international projects pertinent to supporting the safety case.

<u>Major Facilities</u>

No major facilities are required for furthering the study of the specific topic areas discussed in this section.

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