Confidence in Safety - Revell Site - 2023 Update

NWMO-TR-2023-07

December 2023

Nuclear Waste Management Organization

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

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

Confidence in Safety – Revell Site – 2023 Update

NWMO-TR-2023-07

December 2023

Nuclear Waste Management Organization

Document History

Title:	Confidence in Safety – Revell Site – 2023 update		
Report Number:	NWMO-TR-2023-07		
Revision:	R000	Date:	December 2023
Nuclear Waste Management Organization			
Prepared by:	P. Gierszewski, A. Parmenter, A. Lee		
Verified by:	S. Hirschorn, R. Habib		
Approved by:	C. Boyle		

Revision Summary		
Revision Number	**Date**	**Description of Changes/Improvements**
R000	2024-01-25	Release version

EXECUTIVE SUMMARY

The Nuclear Waste Management Organization (NWMO) is presently in a multi-year process of identifying a safe site for a deep geological repository for Canada's used nuclear fuel in an area with informed and willing hosts. This is consistent with plans in other countries with nuclear power programs, including Finland, Sweden, France and Switzerland, which have sites for their deep geological repositories for nuclear fuel waste.

The fundamental safety objective of the project is to protect humans and the environment, including water, from the effects of radioactive or hazardous substances present in the used fuel. The used fuel radioactivity naturally decreases with time. The deep geological repository, including engineered and natural barriers, provides long-term containment and isolation while this natural radioactivity decay occurs.

Previous discussions and studies have identified the Revell Site in northwestern Ontario and the South Bruce Site in southern Ontario as candidate repository sites. Municipalities, First Nations and Métis communities in both siting areas are working with the NWMO as part of the site selection process.

This report focuses on the Revell Site. It summarizes the results as of mid-2023 indicating that this site would be suitable from a technical perspective for hosting a repository. It is intended to support public discussion around site selection.

This report builds on the previous 2022 Confidence in Safety report. It includes in particular new information on the geology, design and safety assessment.

This report is part of a larger site assessment process. Ongoing and future technical work will include further site studies, design development and safety analyses to confirm and extend the results to date. These would ultimately be presented to Canadian federal regulators for an Impact Assessment and a series of Canadian Nuclear Safety Commission (CNSC) licence applications. This is a process that will take years before approval to construct is received. During construction and operations, there will be continued monitoring to ensure that the site is, and remains, suitable for long-term containment and isolation of used nuclear fuel.

The NWMO's assessment of the suitability of the Revell Site is based on site-specific results acquired to date, as well as regional information, the intrinsic characteristics of the repository multiple barrier approach, and from similar projects in other countries. The Revell Site is within the Revell batholith, a rock with favourable characteristics, including a near-homogeneous granitoid composition.

The NWMO is confident that a repository located within a range of 650 m to 800 m below ground surface at the Revell Site will allow for safe repository construction and operation phases, and that the used nuclear fuel will remain isolated from the surface and near-surface environment for sufficiently long times.

The rationale is described in more detail within this report, but key points are as follows:

1. The favourable characteristics of the geology at the Revell Site.

    - The Revell batholith formed about 2.7 billion years ago. It is approximately 40 km long, 15 km wide, and estimated to be about 3 km deep at the site. The Revell Site is in the northern portion of the batholith and boreholes reaching up to one kilometre below surface confirm that this natural barrier system has the depth, breadth, and volume to isolate the repository from surface disturbances and changes caused by human activities and natural events.

    - The granitoid rocks beneath the Revell Site are similar to those of other crystalline rocks of the Canadian Shield, and also of the Fennoscandian Shield, which are the host rocks for repositories in Finland and Sweden. While no direct in situ stress information is yet available for the Revell Site, it is expected that stable bedrock stress conditions are likely to be encountered below approximately 600 m depth. These other sites, as well as site-specific data, provide confidence that the rocks underlying the Revell Site can remove the heat generated by radioactive decay of the used fuel and withstand both natural stresses and thermal stresses.

    - The composition of groundwaters, and of porewaters extracted from core samples, indicate freshwater conditions in the upper part of the bedrock, to approximately 300 m depth, that gradually transitions to brackish and saline conditions between approximately 600 and 650 m below ground surface. The hydrogeological regime within and below this zone of geochemical transition indicates low groundwater velocities in areas of low permeability rock mass away from potentially flowing fracture zones. These favourable hydrogeochemical and hydrogeological indicators support the long-term containment and isolation capability of the site.

    - Durability of the used fuel container is favoured by the site-specific mineralogical and lithogeochemistry data to date, which do not indicate the presence of sulphur-bearing minerals (e.g., sulphides, sulphates) in any appreciable quantities. Also, for all groundwater samples collected to-date, the total dissolved sulphide concentrations were very low. Finally, oxidizing conditions have not been encountered at repository depth.

2. The stability of the geosphere.

    - The Revell Site is within the Revell batholith, a large body of granitoid rock about 2.7 billion years old. The Revell batholith is in the Canadian Shield at the heart of the North American continent. This is a stable, seismically quiet setting, far from tectonic plate boundaries and therefore is not prone to large earthquakes and recent volcanic activity.

    - There is no indication that the Revell Site location will experience extreme rates of erosion, uplift or subsidence that would significantly perturb the geosphere over the next million years.

    - Paleoclimate modelling provides estimates of the impact of future glaciations, including maximum ice and permafrost thickness. Model results align with site-specific observations, including very long groundwater residence times suggested by noble gas concentrations, to indicate that the containment and isolation functions of the geosphere will be maintained at the repository depth.

3. The low risk of inadvertent future human intrusion into the repository.

   - The Revell Site is in Canadian Shield crystalline rock. Petroleum and coal resources are not encountered in these types of rocks.

   - There are no expectations nor indications of mineral resource potential at the Revell Site based on past exploration and current site borehole data.

   - Practical freshwater supplies are encountered in the near surface environment, with deeper waters more saline and not attractive for potable water supply.

4. The site is amenable to geological characterization.

   - The Revell batholith was expected to be a relatively homogenous rock mass. Data from the boreholes confirm the lithological homogeneity of the bedrock at the Revell Site with ~95% of the drill core recovered classified as biotite granodiorite-tonalite, and the remainder including subordinate rocks such as mafic (amphibolite) sheets, and felsic intrusive rocks ranging between tonalite and granite in composition.

   - The data acquired at the Revell Site indicate that the orientations of lineaments at the surface on a larger scale are also present in the orientations of fractures in the boreholes at a smaller scale. This understanding provides confidence in the ability to develop meaningful fracture network models on different spatial scales for the site.

   - Available site-specific data and natural analogue information suggest that stable bedrock stresses are expected, and a stable hydrogeochemical environment with favourable hydrogeological properties will be encountered, at the proposed repository depth beneath the site. These characteristics will support a safe environment for construction, operation, and long-term containment and isolation during the post-closure phase.

5. The robustness of the multiple barrier system.

   - In addition to the favourable geosphere as noted above, the repository includes a series of engineered barriers, in particular the fuel itself, the durable copper-coated containers and bentonite-clay based seals. Studies in Canada and around the world for several decades have provided a strong scientific basis for the safety of deep geological repositories designed around these barriers.

   - Natural analogues provide evidence that the engineered barrier materials, notably the copper, clay and uranium oxide, are durable over very long times under repository-appropriate geological conditions.

   - The placement rooms, access tunnels, shafts and boreholes will all be backfilled and sealed at closure.

6. The ability to safely construct and operate the repository.

   - The rock mass properties are typical of sparsely fractured, high quality, strong, crystalline rocks. The rock is suitable for safe underground construction and operation.

- The Revell Site has suitable surface area for the construction and operation of surface facilities and excavated rock management area.

- The site is near the top of a watershed, and the facilities can be sited and designed to avoid risk of site flooding.

- The Revell Site has suitable underground area for placement of the projected used fuel from Canada's existing nuclear fleet. The site also has some expansion capacity.

- A preliminary conceptual design has been developed for the repository facilities. It is presently being adapted to the site-specific conditions.

- The NWMO Proof Test program is demonstrating the ability to fabricate, handle and place the underground fuel containers. It is informed by related tests in other countries.

- The Revell Site is within 10 km of Trans-Canada Highway 17, the Canadian Pacific rail line, electrical transmission towers, and the TransCanada Canadian Mainline natural gas pipeline.

7. The used fuel can be safely transported to the repository.

- The NWMO has a licenced transport package already available for CANDU used fuel. This package is designed and tested to withstand severe accidents. Used fuel has been safely transported in Canada and in other countries for over 50 years.

- The Revell Site is within 10 km of a highway and rail line. Road and rail infrastructure could be established to the site to support those modes of transport. An all road and a road/rail combination transportation system are technically feasible for the site.

8. Facility performance will meet regulatory criteria for safety and the protection of the environment.

- All countries which have decided on the long-term management of their used fuel have plans for a deep geological repository for this purpose.

- The Canadian regulatory framework has defined steps and expectations for licensing a repository. It is consistent with international best practice.

- A preliminary site-based safety assessment indicates that there would be no impacts on human health during operations or post-closure. The results are similar to safety assessment studies to date for other crystalline rock sites, which have indicated that a repository in these rock types can perform well.

- Baseline monitoring is in-place or underway, including in deep boreholes and shallow groundwater wells, surface water bodies, seismicity and meteorological conditions, as well as biodiversity studies.

- The site will be monitored for decades during site characterization, preparation, construction and operation, before a decision is made to close the repository. This monitoring will support the repository construction and operations, as well as confirm that the repository is not causing harm to people or the environment.

Overall, based on the assessment results to date, the NWMO is confident that a deep geological repository can be constructed at the Revell Site in a manner that would provide safe long-term management for Canada’s used nuclear fuel.

More site characterization is required and is planned should the site be selected. However, the uncertainties that remain are less about the fundamental suitability of the Revell Site to safely contain and isolate used nuclear fuel, and more about continuing to develop and document a thorough quantitative understanding of the site.

Uncertainties remain in the following areas, which will be addressed in the next phase of site characterization and design activities:

- Geometry and property of fractures at depth, in particular gently-inclined and water-conducting fractures related to subordinate rock types present in the granitoid bedrock. This will require additional study to enhance confidence in groundwater flow and radionuclide transport modelling.

- Likelihood and potential impact of post-glacial faulting. While the Revell Site is located in a region of low seismic hazard, microseismic monitoring is on-going to determine if any active faults are present in the region around the site and an investigation of potential recent fault activity will be conducted as part of future detailed site characterization.

- Further site specific properties are needed to finalize the design. This includes rock properties, as well as details of the surface and near-surface environment, such as hydrology. These will support optimizing the site and design to protect the environment during construction and operations.

These uncertainties will also be mitigated through the positioning of repository placement rooms during the underground excavation and by the robustness of the multiple barrier system. The design of the surface and underground facilities will continue to evolve throughout site characterization.

The safety of the proposed site will be confirmed through a rigorous regulatory review of the facility design and safety case. The decision-making process and implementation will extend over decades. Uncertainties can be addressed within the flexibility of the NWMO's program, including aspects such as monitoring and retrievability. The program, evolving over a long period of time, will have the ability to adjust to new information and technologies to improve understanding and optimize performance.

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

ABBREVIATIONS

AECL – Atomic Energy of Canada Limited

APM – Adaptive Phased Management

CANDU – Canada Deuterium Uranium reactor type

CNSC – Canadian Nuclear Safety Commission

DGR – Deep geological repository

EBS – Engineered barrier system

ERMA – Excavated Rock Management Area

GEH BWR – General Electric - Hitachi Boiling Water Reactor

HLW – High-level radioactive waste

IAEA – International Atomic Energy Agency

ILW – Intermediate-level radioactive waste

NWMO – Nuclear Waste Management Organization

OPG – Ontario Power Generation

PAG – Potentially Acid Generating

RQD – Rock Quality Designation

UDF – Underground Demonstration Facility

UFC – Used Fuel Container

UFPP – Used Fuel Packaging Plant

UFTP – Used Fuel Transportation Package

1. INTRODUCTION

1.1 Background

The Nuclear Waste Management Organization (NWMO) is presently in a multi-year process of identifying a safe site for a deep geological repository for Canada's used nuclear fuel in an area with informed and willing hosts (NWMO 2010). This is similar to plans in other countries with nuclear power programs, including Finland, Sweden, France and Switzerland, which have sites for their deep geological repositories for nuclear fuel waste.

The Government of Canada selected the deep geologic repository approach in 2007, and assigned the NWMO with the task of siting, building and operating this repository. The NWMO has responded with a siting program that includes discussions and planning with communities, and conducting technical and social studies. Early assessments were summarized in a series of reports available on the NWMO website at www.nwmo.ca/studyareas.

These discussions and studies have identified two candidate siting areas – one in northwestern Ontario and one in southern Ontario.

This report focuses on the Revell Site in the Wabigoon Lake Ojibway Nation (WLON) – Ignace area. This site is located approximately 21 km southeast of the Wabigoon Lake Ojibway Nation and 43 km northwest of the Town of Ignace. The site is on the Canadian Shield, about 260 km north of Lake Superior (Figure 1.1 and 1.2).

Figure 1.1: Typical landscape at the Revell Site, with Borehole 4 site in the background.

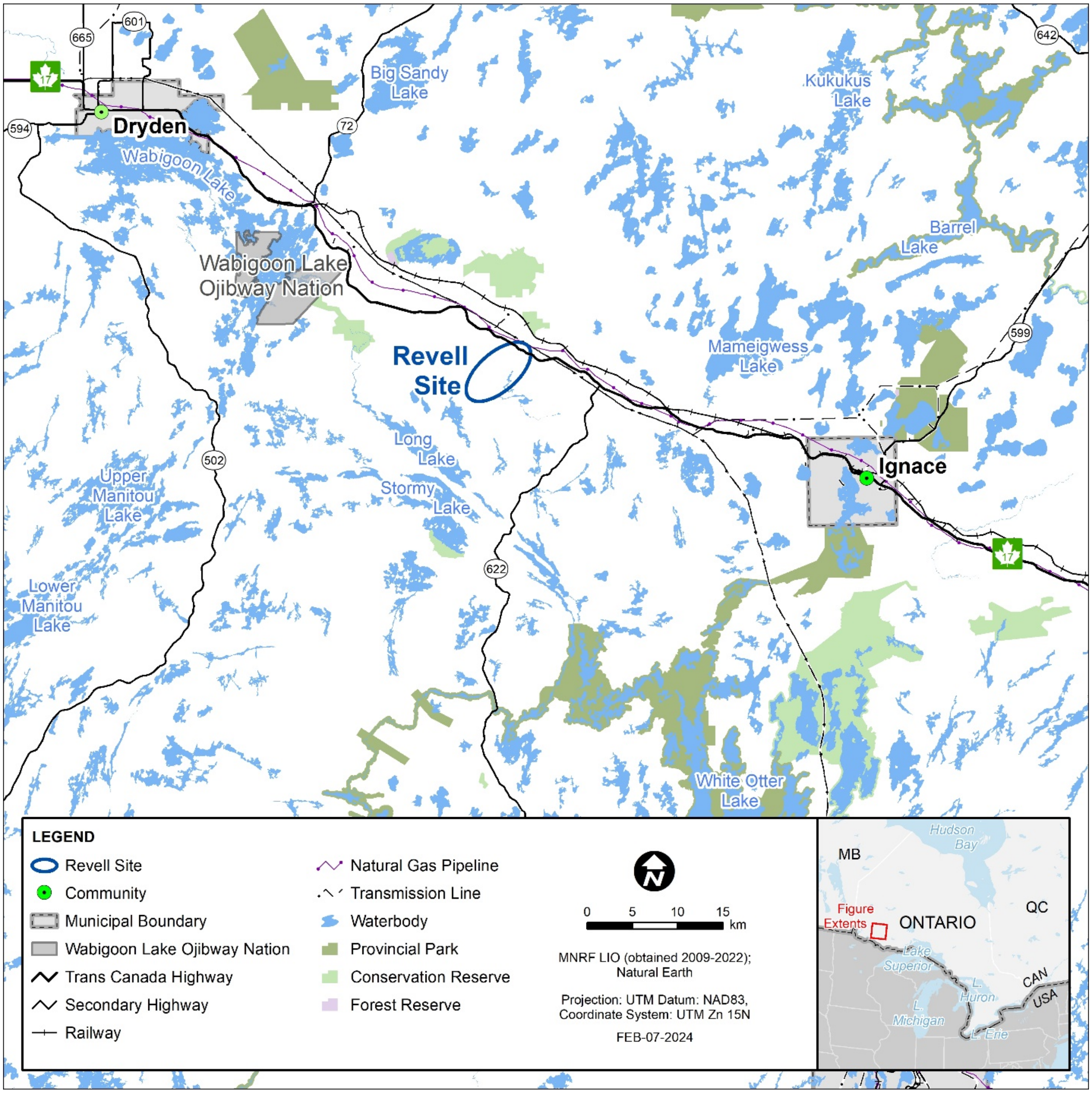

Figure 1.2: General location of the Revell Site in northwestern Ontario. Inset map shows main figure location in Ontario.

1.2 Deep Geological Repository Concept

The fundamental safety objective of the project is to protect humans and the environment, including water, from harmful effects of radioactive or hazardous substances present in the used fuel.

The strategy to achieve this objective is to isolate and contain the radioactive material by placing the used nuclear fuel in a deep stable geologic environment, surrounded by multiple barriers. This strategy is referred to here as a **deep geological repository** (also DGR or repository).

The repository concept is shown in Figure 1.3. The key components are:

- the waste form (i.e., used nuclear fuel);
- the engineered barrier systems, notably the used fuel container and clay seals;
- the host rock;
- the underground repository facilities, notably the shafts, main services area, and the placement rooms connected by access tunnels; and
- the main surface facilities, where fuel is received, packaged, and transferred underground.

The concept also includes the transportation system for moving fuel from interim storage sites to the repository site.

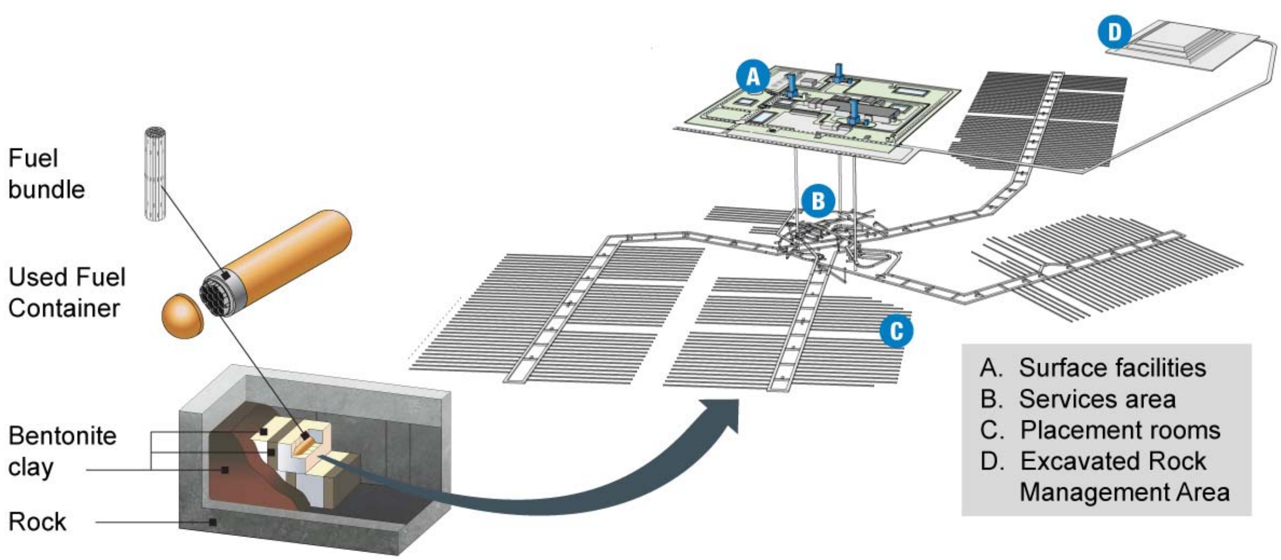

Figure 1.3: Deep Geological Repository concept

1.3 Wabigoon Lake Ojibway Nation (WLON) - Ignace Area

The Revell Site is within the WLON-Ignace area on the Canadian Shield in northwestern Ontario (Figure 1.1 and Figure 1.2).

The WLON-Ignace area comprises broadly rolling surfaces of Canadian Shield bedrock that is either exposed at surface or shallowly covered with glacial deposits. The land surface within the area varies somewhat from the region in that there is considerable relief between the lakes in most areas and the ground surface elevation ranges from 368 metres above sea level where the Wabigoon River intersects the western boundary of the Ignace area to 554 metres in the southeast.

The WLON-Ignace area lies in a transition zone between the boreal and the Great Lakes-St. Lawrence forest. Two major surface soil types exist, clay and sand, and these support conifer and mixed forest types.

The WLON-Ignace area is within the Nelson River Drainage Area, which drains into Hudson Bay through the Nelson River. In the area there are three tertiary watersheds, the Upper English sub-basin, the Wabigoon sub-basin and the Central Rainy sub-basin. The area is abundant in lakes, which are interconnected by an intricate network of small and medium sized rivers, and by large rivers such as the Wabigoon River, Bending River and Gulliver River.

The Revell Site is within the Wabigoon sub-basin and is drained by the Wabigoon River to the northwest.

Water wells in the WLON-Ignace area obtain water from the overburden or the shallow bedrock. Some communities obtain water from nearby lakes.

Further information on the environment is provided in the NWMO Phase 1 Assessment report (NWMO 2013). This information is presently being updated as part of the NWMO site baseline studies and environmental baseline monitoring program.

1.4 Purpose of Report

This document presents the current basis for the NWMO's confidence that a deep geological repository could be constructed at the Revell Site in a manner that would provide safe long-term management of Canada's used nuclear fuel. This confidence is built on our understanding of the following aspects:

- the characteristics of the geology of the Revell Site that provide containment and isolation;
- the long-term stability of the geosphere;
- the low risk of future human intrusion into the repository;
- the site is amenable to characterization;
- the robustness of the multiple barrier system;
- the repository can be constructed, operated and closed safely;
- the used fuel can be safely transported to the site; and
- the facility performance will meet regulatory criteria for safety and environmental protection.

This report presents the safety basis and the associated uncertainties as they stand as of mid-2023. Our understanding of the site is based on observations from site investigations over the past several years, including initial results from drilling, coring and testing of six deep boreholes at the site, as well as installation and monitoring of a network of shallow groundwater wells and of microseismic stations, and a 2D seismic survey. More site characterization is required, and is planned, should the site be selected. However, the uncertainties that remain are less about the fundamental suitability of the Revell Site to safely contain and isolate used nuclear fuel, and more about developing and documenting a thorough quantitative understanding of the site.

In this report, current technical information is provided to support public dialogue and community confidence building for proceeding to the next stage of site selection. The statements made here are supported by more than 50 site-specific technical reports produced as of mid-2023 (Appendix A), as well as other reports that are in preparation.

It is not a final safety report, with the level of detail and completeness needed for obtaining approvals by the regulatory authorities.

This report is part of a stepwise approach. Site characterization, design development and safety analyses are continuing, which will further check and clarify the safety basis. If this site is formally proposed for the repository, these would eventually be documented in a series of reports that support an Impact Assessment and the first licence application for Site Preparation.

2. NATURE OF THE USED FUEL

Almost all of the used nuclear fuel in Canada (about 99.9%) is produced by CANDU nuclear power reactors in Ontario, Québec and New Brunswick. There are also very small quantities of used fuel from research, demonstration and isotope-producing reactors, largely at the Chalk River Laboratories site in Ontario (NWMO 2022). Ontario Power Generation (OPG) is now planning to build a GEH BWRX-300 Boiling Water Reactor (BWR) at its Darlington site with a licence to construct application submitted.

The fuel for CANDU power reactors is solid uranium dioxide (UO_2) (Figure 2.1), as is the fuel for a GEH BWR reactor. This is similar to uraninite, a common naturally occurring form of uranium, such as found in Canadian uranium ore bodies.

This UO_2 is pressed into a dense ceramic pellet and sealed inside metal tubes made of zirconium alloy. These tubes (called fuel elements) are welded together into a CANDU fuel bundle (Figure 2.1) or a fuel assembly. The bundle characteristics vary slightly between the different CANDU reactors. The Bruce and Darlington 37R fuel bundle, which is the most common to date, contains 37 fuel elements and weighs 23.9 kg, of which 21.7 kg is UO_2 and 2.2 kg is Zircaloy. The GEH BWR fuel assemblies are about 4.5 m long, and weigh about 300 kg.

Other nuclear fuels and waste forms are being proposed in Canada as part of a new generation of nuclear reactors. Any nuclear fuel wastes intended for this repository from new reactors would only occur some decades in the future. At this time, the details of these wastes are not well known, but would need to be included in an engineered barrier system that ensures long-term safety.

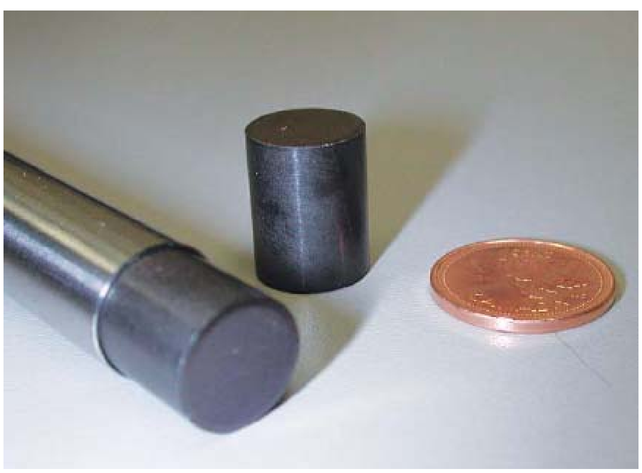

Figure 2.1: (Left) Ceramic UO_2 fuel pellets before irradiation, and pellets fitting inside Zirconium alloy cladding. (Right) Typical CANDU fuel bundle before irradiation.

In a reactor, heat is produced by **fission**. Fission occurs within the fuel when a neutron is absorbed by certain heavy atoms (notably U-235), which then split into two smaller atoms (called **fission products**). Neutrons are also released during fission, sustaining the nuclear chain reaction.

New atoms are also generated in the reactor when an existing atom absorbs a neutron, a process called neutron capture or activation. Some new atoms are heavier than uranium, such as plutonium. Collectively, these heavy atoms including uranium are called **actinides**.

Many of the new atoms formed are unstable, i.e., they are **radioactive** atoms or **"radionuclides"**. In this process, the atom spontaneously releases energy, and changes into a different type of atom, a process called **radioactive decay** or **radioactivity**. This decay energy is released as various types of **radiation**, including alpha, beta and gamma radiation. Eventually, all radioactive atoms decay into stable atoms and do not release further radiation. This radioactive decay is a natural process. It can take anywhere from fractions of a second to occur, to longer than one million years, depending on the particular type of atom. Radioactivity is measured in **Becquerels (Bq)** where 1 Bq is one atom decay per second. Uranium is an example of a naturally occurring radioactive atom.

Before entering the nuclear reactor, the UO_2 fuel consists primarily of uranium and oxygen atoms (inside zirconium alloy metal). On leaving the nuclear reactor, the fuel (now called spent or **used fuel**) still contains mostly uranium and oxygen, but also small amounts of other atoms produced by fission and neutron capture as outlined above. The characteristics of the used fuel depend on the nature of the reactor operation. This operation is often described in part by the **burnup**, which is the cumulative amount of energy released per unit mass of uranium. The burnup range of CANDU fuel is about 120-320 MWh/kg U, with a median burnup value of about 200 MWh/kg U. At this burnup, about 2% of the initial uranium has been "burned" and converted into other atoms. GEH BWR fuel is designed for higher burnup of about 1200 MWh/kg U.

Table 2.1 provides a summary of the most abundant atoms in typical CANDU fuel by weight, before and after irradiation.

When the used fuel is removed from the reactor, it is highly radioactive and generating radiation. The radioactivity (and radiation) initially decreases very quickly with time. For the first 7-10 years after removal, the used fuel is stored at the reactor site in fuel bays (closed water pools) which provide radiation shielding and cooling. After this time, the used fuel can be stored in air-cooled concrete containers (referred to as dry storage).

The total radioactivity of used fuel decreases with time after the fuel is discharged from the reactor as illustrated in Figure 2.2. The total radioactivity drops by a factor of 1000 over the first 10 years. Over the next 500 years, the fission product radioactivity drops significantly. At this point, the remaining radioactivity is mainly due to the actinides present in the used fuel. The total radioactivity continues to decay slowly. After about 1 million years, the radioactivity in the used fuel is primarily due to the natural radioactivity of uranium. The total mass of uranium and total radioactivity in the repository would be similar to that in large Canadian uranium ore bodies.

Table 2.1: Composition of fresh and used CANDU UO_2 fuel bundle (220 MWh/kgU burnup, 30 years since discharge)

Component *	Fresh (Unirradiated) Bundle	Used Bundle
	Bundle Mass %	**Bundle Mass %**
Actinides		
U-238	79.41%	78.60%
Pu-239	-	0.22%
U-235	0.58%	0.14%
Pu-240	-	0.10%
U-236	-	0.06%
Th-232	0.04%	0.04%
Am-241	-	0.02%
Pu-242	-	0.01%
Pu-241	-	0.01%
U-234	0.004%	0.003%
Other Actinides	-	0.005%
Other Elements and Fission Products		
O (stable)	10.73%	10.79%
Zr (stable), incl. Zr-96	8.93%	9.01%
Sn (stable)	0.16%	0.16%
Xe (stable)	-	0.13%
C (stable)	0.07%	0.07%
Mo (stable)	-	0.05%
Ce (stable)	-	0.05%
Ru (stable)	-	0.05%
Nd (stable)	-	0.05%
Ba (stable)	-	0.04%
Cs (stable)	-	0.03%
Nd-144	-	0.03%
Mo-100	-	0.02%
Tc-99	-	0.02%
Zr-93	-	0.02%
Cs-137	-	0.01%
I-129	-	0.004%
Other Radionuclides	-	0.04%
Others Stable Isotopes	0.09%	0.24%

*Includes impurities naturally present in fuel

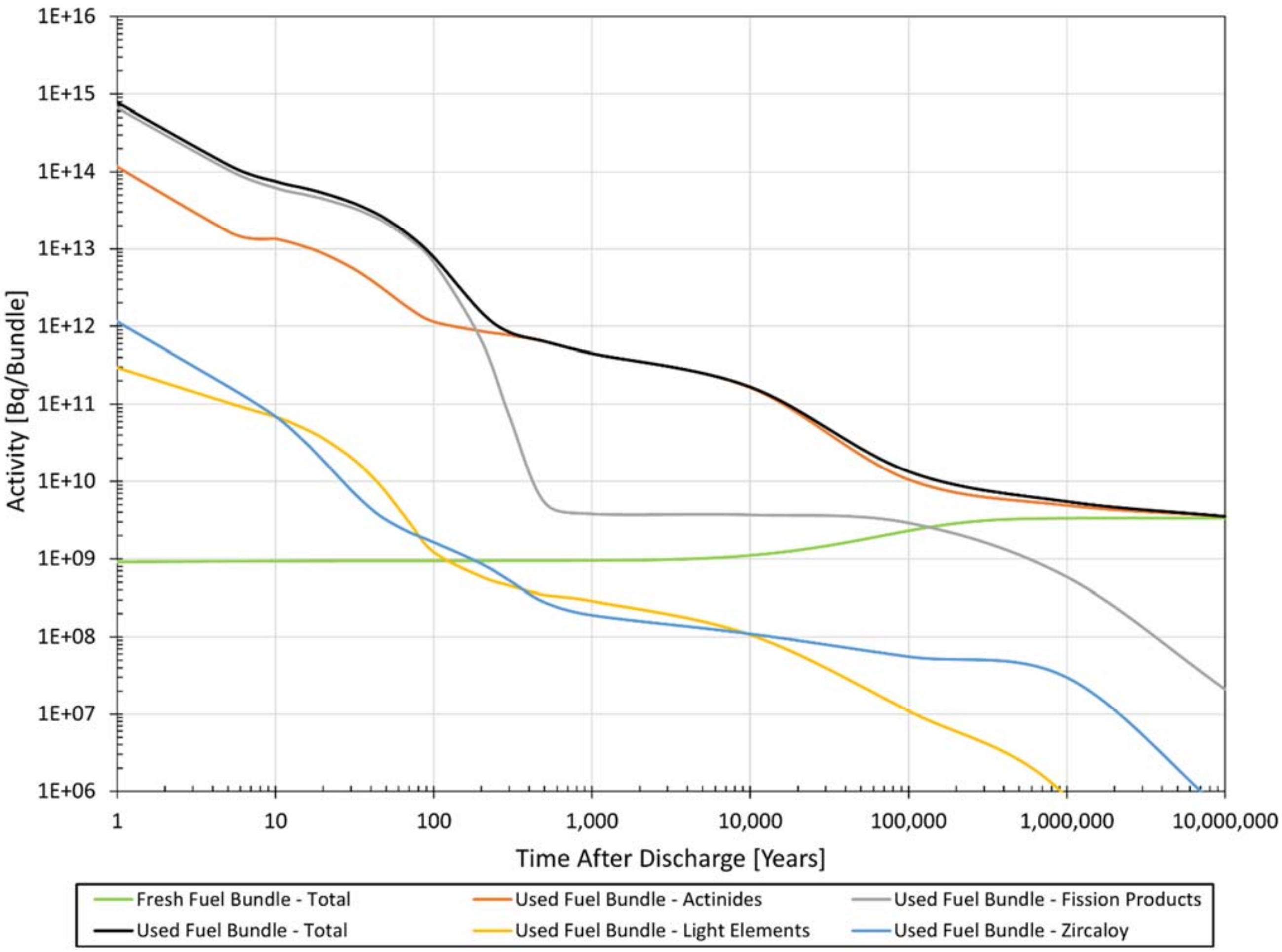

Figure 2.2: Radioactivity of used CANDU fuel decreases with time (fuel burnup of 220 MWh/kgU)

The hazard from used fuel is primarily due to the radiation released by radioactive atoms in the used fuel. Radiation is energy travelling through space. Used fuel releases energy primarily as thermal radiation (heat) and as alpha, beta, gamma and neutron radiation. The latter four are referred to as nuclear radiation or ionizing radiation.

Alpha and beta radiation cannot penetrate far, the fuel bundle cladding stops most of them. They are a hazard if they are ingested or inhaled.

Gamma and neutron radiations can penetrate outside of the used fuel. However, they can be stopped with sufficiently thick layers of dense material, referred to as **shielding**. Figure 2.3 shows CANDU used fuel storage in a reactor fuel bay and in steel-and-concrete canisters (dry storage). These illustrate how several metres of water or tens of centimetres of concrete and steel can provide shielding from the radiation from used fuel.

In a deep geological repository, used fuel is placed so deep underground that there is no exposure to humans or the environment at surface. The several hundred metres of rock above the repository provide more than sufficient shielding from the gamma and neutron radiation.

Figure 2.3: Photos of workers in CANDU used fuel bay and in dry storage facility.

The radioactive atoms are embedded within the used fuel, which are in turn contained within other engineered and natural barriers. These barriers include the used fuel container, the surrounding clay layer and the several hundred metres of rock above the repository. Exposure of people to these atoms would be highly unlikely as it would require the failure of multiple barriers, occurring before these atoms had decayed to non-radioactive atoms. The durability of the barriers is supported in part through natural analogue evidence noted in Section 9.

In the highly unlikely event of multiple barrier failures, some of these radioactive atoms could reach the surface environment, and could cause radiation dose to plants, animals and humans. A possible exposure would be through ingestion of food or water that contains radioactive atoms. Analysis indicates that the total internal hazard of the fuel follows the same general shape as the radioactivity in Figure 2.2. It decreases significantly over the first 1000 years, and is due largely to fission products. From 1000 to 100,000 years, it is largely due to actinides such as plutonium. After one million years, the remaining hazard is largely due to the decay products of the uranium within the used fuel. After this time, the hazard of a repository is comparable with that of naturally occurring large uranium ore bodies. These ore bodies exist in a variety of locations around the world, and may not be noticeable at surface when the ore bodies are underground (e.g., Cigar Lake, Canada, per Cramer and Smellie 1994).

The health effects of radiation on humans are quantified using **sieverts**, a unit of radiation dose that depends on the amount and type of ionizing radiation absorbed and the type of human tissue exposed. One millisievert (mSv) is one-thousandth of a sievert.

People are constantly exposed to naturally occurring radioactivity in the ground and water and air around us, and to natural radiation coming from space. The average Canadian receives a dose of about 1.8 mSv each year from these natural sources (Grasty and LaMarre 2004). The Canadian nuclear regulator sets limits on the additional dose that the public can receive from non-medical man-made sources, essentially limiting this to 1 mSv per year maximum and in practice much lower. The dose from living near a repository would be much lower than this limit, as discussed in Section 10.

3. LONG-TERM GEOLOGICAL CONTAINMENT AND ISOLATION

The repository must contain and isolate the used nuclear fuel. To ensure this, the geoscientific conditions (properties and processes) of the Revell Site should:

- promote long-term isolation of used nuclear fuel from humans, the environment and surface disturbances;
- promote long-term containment of used nuclear fuel within the repository; and
- restrict groundwater movement and retard the movement of any released radioactive material.

The ability of the Revell Site to safely contain and isolate the used nuclear fuel can be assessed through the following site evaluation factors (NWMO 2010):

1. The depth of the host rock should be sufficient for isolating the repository from surface disturbances and changes caused by human activities and natural events.

2. The volume of available competent rock at repository depth should be sufficient to host the repository and provide sufficient distance from active geological features such as zones of deformation or faults and unfavourable heterogeneities.

3. The mineralogy of the rock, and the geochemical composition of the groundwater and rock porewater at repository depth should not adversely impact the expected performance of the repository multiple-barrier system.

4. The hydrogeological regime within the host rock should exhibit low groundwater velocities.

5. The mineralogy of the host rock, the geochemical composition of the groundwater and rock porewater should be favourable to retarding radionuclide movement.

6. The host rock should be capable of withstanding natural stresses and thermal stresses induced by the repository without significant structural deformations or fracturing that could compromise the containment and isolation functions of the repository.

Each of these factors are discussed in the subsections below and in Sections 4 and 5.

The NWMO has developed an understanding of the bedrock in the WLON-Ignace area, including the Revell batholith at surface, and at depth beneath the Revell Site, based on the collection, evaluation, and modelling of data during site characterization studies that were initiated in 2010 and are still underway. To date these include:

- 2011 - Initial Screening desktop study (Golder 2011)

- 2012-2013 - Phase I Desktop preliminary assessment (Golder 2013)

- 2014-2016 - Initial Phase 2 preliminary assessment field studies, including high-resolution airborne geophysical surveys (SGL, 2015) and geological mapping (SRK and Golder 2015).

Between 2017 and 2023 the site investigations have focused primarily on characterizing the Revell Site and surrounding area, including:

- High-resolution airborne LiDAR measurements of the surface topography (ATLIS 2018)
- Structural lineament interpretation (DesRoches et al. 2018), two-dimensional (2D) bedrock geological map (Parmenter et al. 2020), and three-dimensional (3D) geophysical/geological model (SGL 2020) for the Revell Site and surrounding area
- Drilling, coring, and testing, of six deep boreholes, with on-going long-term monitoring and sampling in four boreholes
- Installation and on-going monitoring of nine shallow groundwater wells
- 2D seismic reflection survey (Vibrometric 2022), and vertical seismic reflection profiles completed in three deep boreholes (WSP-Golder 2022; WSP 2023a,b)
- Installation and on-going monitoring of nine microseismic stations, and additional geological mapping.

In addition, knowledge about the expected behaviour of granitoid rocks, both specific to the Canadian Shield geological setting and from around the world, is used by the NWMO to develop an understanding of the Revell batholith at the Revell Site. This includes information from Canadian academic, geological survey and mining industry sources, as well as from international academic and nuclear waste management organizations. Together with the site-specific information gathered to date, this natural analogue information provides a strong basis for demonstrating the long-term geological containment and isolation potential of the Revell batholith.

3.1 Geology of the Revell Site

The Revell Site is located in the **Revell batholith** in northwestern Ontario, in the geological **Wabigoon Subprovince** of the Canadian Shield. The Revell batholith is a rock unit approximately 40 km in length and 15 km in width formed by the solidification of a volume of magma that intruded into continental crust about 2.7 billion years ago (Percival and Easton 2007). Batholiths are common in the Canadian Shield and are potentially suitable for hosting a deep geological repository as they often are relatively uniform in their composition and show a relatively low degree of deformation and fracturing. The Revell batholith is surrounded by greenstone belts, which are geological complexes composed of older volcanic and sedimentary rocks that have undergone higher degrees of deformation and metamorphism.

Figure 3.1 shows the 2D bedrock geology at the surface in and around the Revell Site, including the Revell batholith and surrounding greenstone belts. The Revell Site is where most of the recent geoscientific site-specific studies have focused. The site is approximately 19 km^2 in size and situated in the northern portion of the Revell batholith.

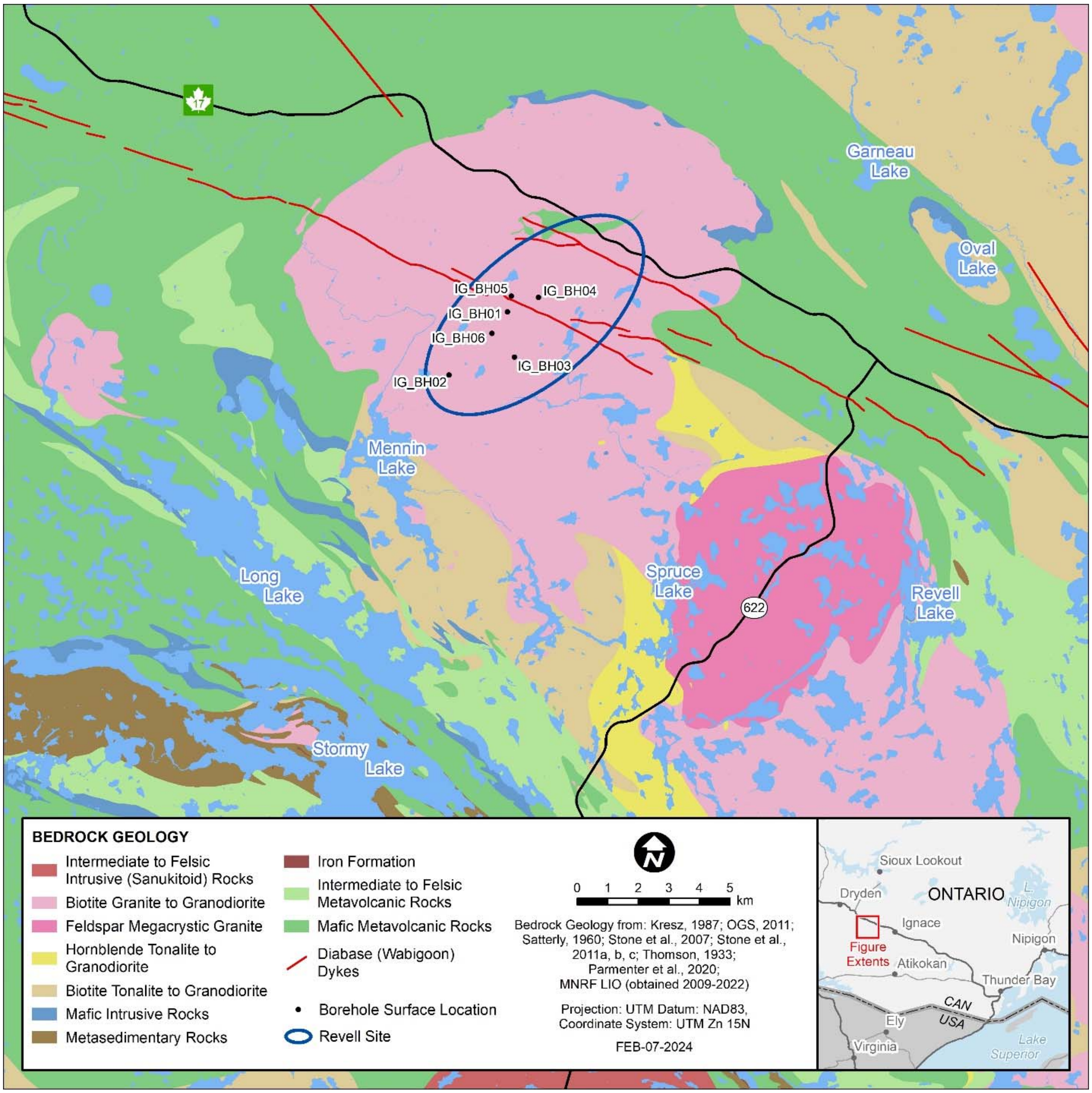

Figure 3.1: Surface bedrock map of the Revell area. The Revell Site is outlined with blue oval.

A 3D geophysical/geological model for the Revell regional area (SGL 2020) has been developed based on high-resolution geophysical surveys and the surface geological data (Figure 3.2). The Revell batholith has been modelled with a relatively flat base that extends to a depth of nearly 4000 m in some regions. In the northern portion of the Revell batholith where the Revell Site is located, the potential host rock is estimated to be 2500 to 3000 m thick. This is much deeper than would be needed to host a repository.

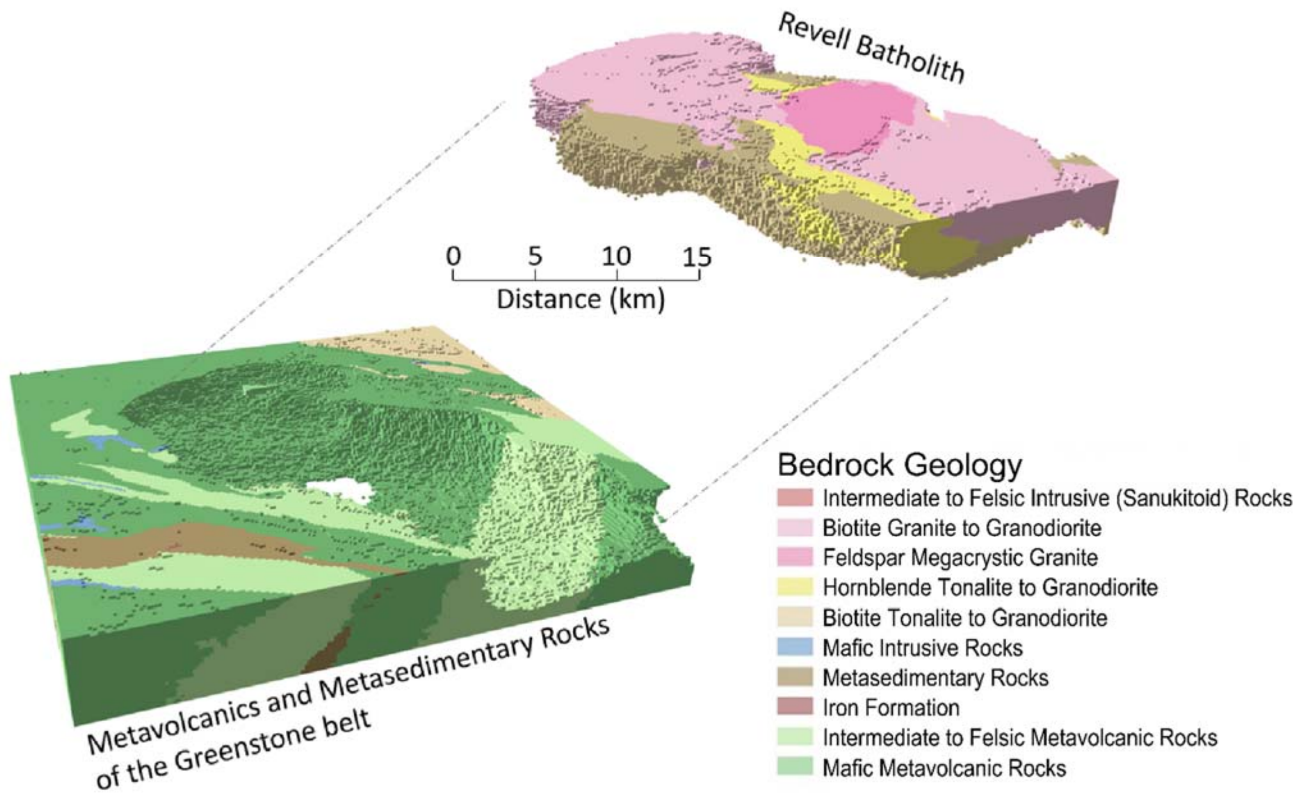

Figure 3.2: 3D geological model of the Revell area. The Revell batholith at top right has been removed from the surrounding greenstone belt rocks at bottom left for visualization purposes. The open white space in the centre of the bottom left image indicates the lower boundary of the model, at 4000 m below ground surface.

Two campaigns of geological mapping at the surface across the Revell Site indicated the presence of near-homogeneous granitoid composition rocks dominated by biotite granodiorite-tonalite (referred to throughout the remainder of this report as granodiorite-tonalite), and with a generally low frequency of fractures at outcrop scale (SRK and Golder 2015; Golder and PGW 2017). Additional data was collected from six deep boreholes drilled to a maximum depth of 1000 m. The borehole locations are indicated in Figure 3.1. Approximately 95% of the drill core recovered is granodiorite-tonalite, consistent with the surface observations and confirming that the same bedrock at surface extends to at least 1000 m depth (Figure 3.3; Parmenter et al. 2022a,b,c).

Uranium-lead (U-Pb) isotope analysis of the mineral zircon from granodiorite-tonalite core samples yielded a mean age of 2.71 billion years (Davis 2023), which is consistent with the expected age for the northern portion of the Revell batholith based on prior regional geological understanding. This old and near-homogenous granitoid rock is the primary natural barrier for a repository beneath the Revell Site.

The remaining volume of bedrock includes approximately 2.5 % of felsic igneous rocks varying in composition between tonalite and granite, and approximately 2.5 % of mafic igneous rocks, including a suite of metre-scale bodies with sheet-like geometry. During core logging these mafic sheets were assigned the preliminary field term of amphibolite. Further work is on-going to better understand these distinct rock type(s) and their geological significance, and throughout the remainder of this report they will be referred to as amphibolite.

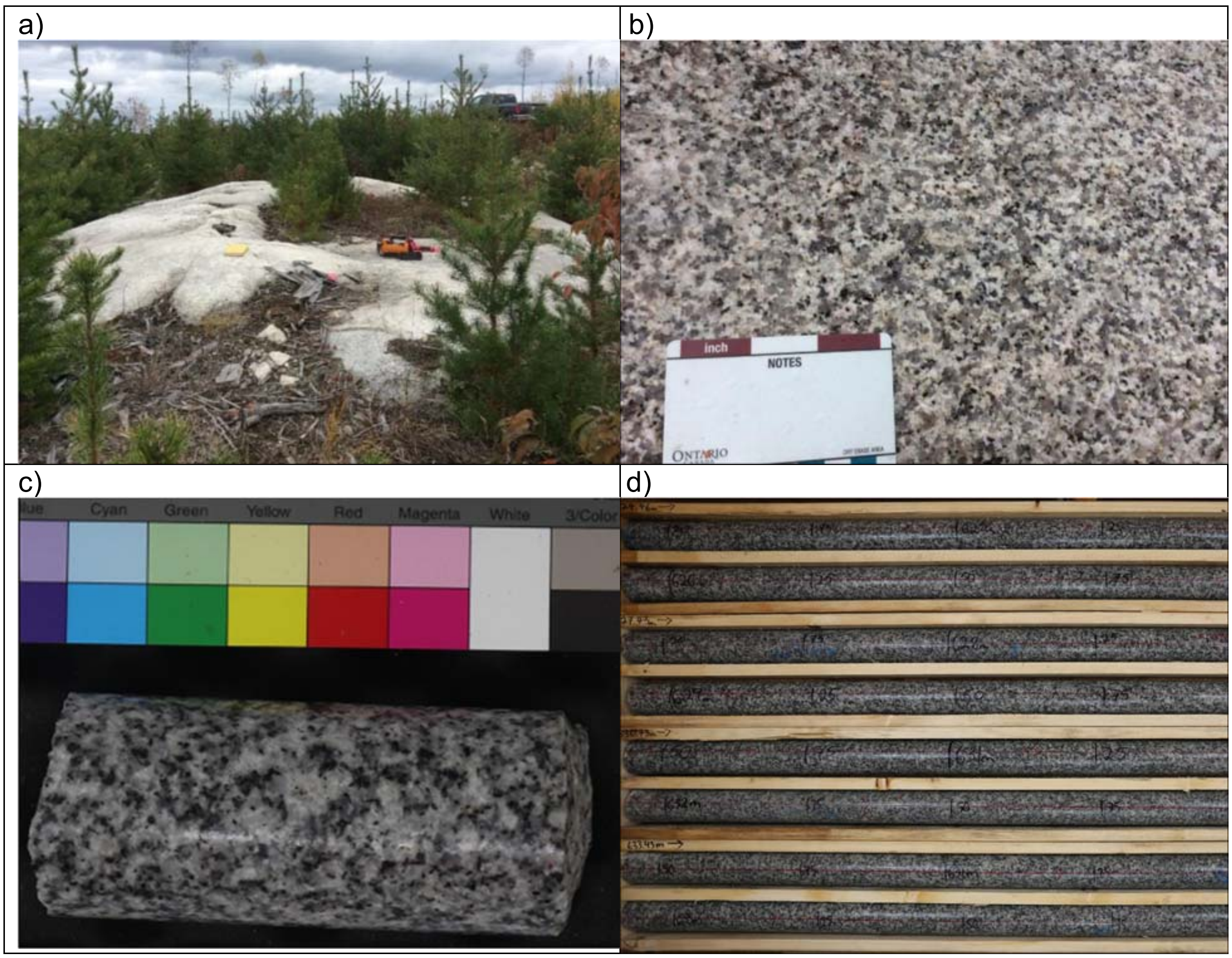

Figure 3.3: Examples of granodiorite-tonalite at the Revell Site. (a) at outcrop scale with yellow notebook for scale, (b) close-up of exposed bedrock with scale card, in inches, and (c, d) in core recovered from the deep boreholes. Core cylinders in (c, d) are 61 millimetres in diameter.

The other distinct mafic rock identified at the Revell Site is an approximately 15-20 m wide mafic diabase dyke that extends across the northern portion of the batholith (Figure 3.1 and Figure 3.5). This larger dyke is associated with several other similarly-oriented mafic dykes that stretch across the northern portion of the Revell batholith and into the surrounding greenstone belts. All of these mafic dykes have a similar character, including a near-vertical orientation, and are interpreted to be part of the Wabigoon diabase dyke swarm. One sample from the same Wabigoon diabase dyke swarm yielded a measured (U-Pb) age of 1.89 billion years old (Stone et al. 1989), indicating that these dykes are younger than the other rocks at the Revell Site.

Sub-horizontal to shallowly-dipping, thin amphibolites are evident from borehole observations, from the 2D seismic reflection data (Vibrometric 2022), and from vertical seismic reflection profiling (VSP) data collected in boreholes labelled IG_BH04, IG_BH05 and IG_BH06 (Figure 3.4; WSP-Golder 2022; WSP 2023a,b). The amphibolites, and some felsic dykes, are spatially associated with increased density of fractures, and a small subset of the sub-horizontal to gently-inclined fractures close to or along contacts to the granodiorite-tonalite are identified as pathways for groundwater flow. The amphibolites also have a slightly lower thermal conductivity than the surrounding granitoid bedrock (e.g., Golder 2022a). Based on the geological model developed to date (DesRoches et al. 2021), it is understood that amphibolites will be encountered during excavations at 650 – 800 m depth, if the Revell Site is chosen as the site for a deep geological repository. While some uncertainty remains regarding the nature and distribution of these amphibolites beneath the site, their presence does not significantly impact the overall suitability of the rock.

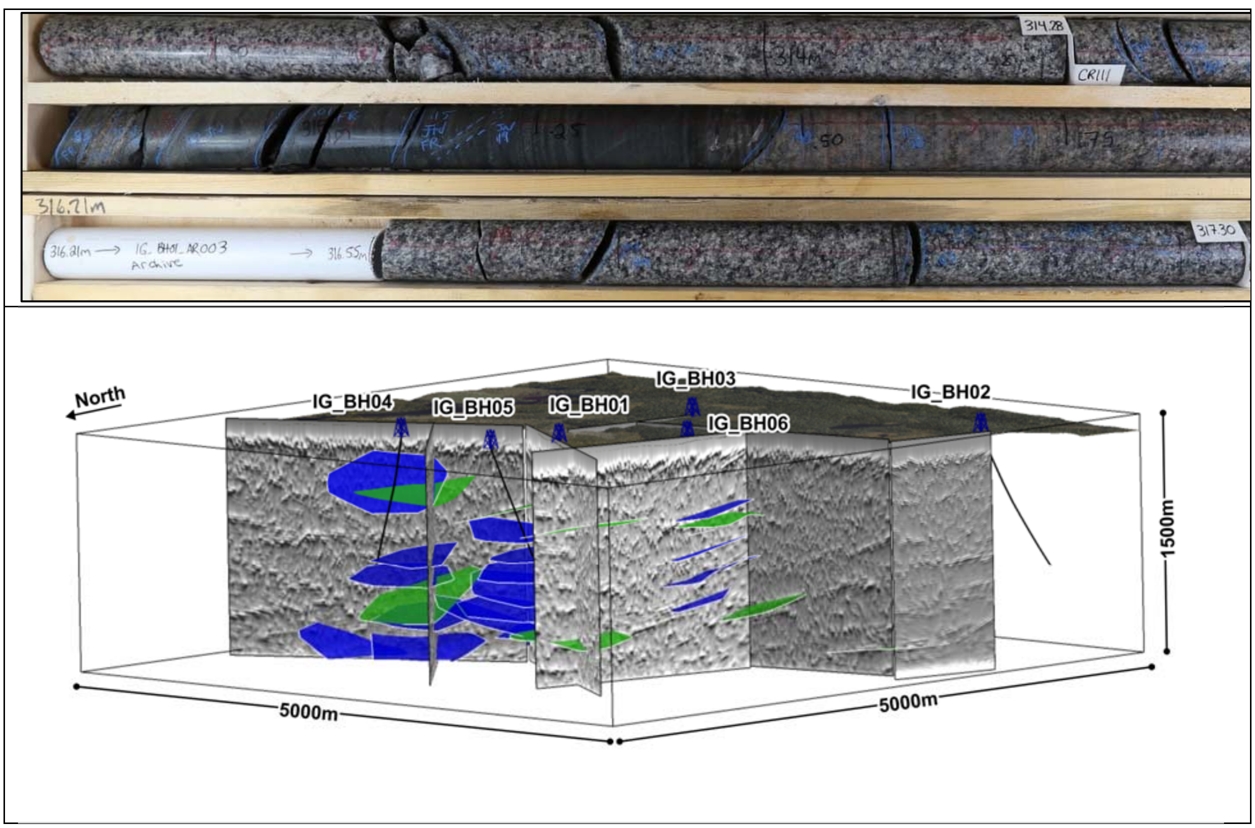

Figure 3.4: Examples of amphibolite at the Revell Site in: (a) core recovered from the boreholes, and (b) interpreted surfaces derived from the 2D seismic and VSP reflections.

The 2D seismic and VSP investigations further found that bedrock with similar seismic characteristics, including reflections attributed to the occurrence of amphibolite sheets, extends to at least 1500 m below ground surface (Vibrometric 2022). This data supports the understanding that the same bedrock identified in boreholes can be imaged with high confidence in the bedrock away from the boreholes.

Geological mapping in the Revell batholith, including at the Revell Site, also identified and characterized fractures and other planar features of different sizes at surface. Parts of these features were not directly visible but inferred to exist or connect based on other information, including remote sensing data, leading to a set of interpreted surface features referred to as lineaments (DesRoches et al., 2018). Some of these interpreted lineaments extend for tens of kilometres. Geological mapping of several of these long lineaments shows them to be relatively discrete, metre-scale zones of structural damage to the bedrock (Golder and PGW 2017). Figure 3.5 shows the distribution of interpreted lineaments in proximity to the deep boreholes at the Revell Site.

Interpreted lineaments show potential, or inferred, fracture zone locations at surface. The data acquired at the Revell Site indicate that the orientations of lineaments at the surface on a larger scale are also present in the orientations of fractures logged in the boreholes at a smaller scale. This analysis supports the assumption that lineaments correspond to fracture zones in the bedrock. Such fracture zones were commonly encountered during drilling as intervals of increased brittle structural complexity with associated increased fracture frequency. In some occurrences, fracture zones include ductile fabrics reactivated by (or which caused the nucleation of) brittle fractures. Direct analysis of core from the boreholes indicates a relatively low degree of fracturing away from these features, except in proximity to amphibolite sheets and other subordinate rock types, where similar increased ductile and or brittle structural complexity is commonly observed. These observations suggest that the presence of large fracture zones and subordinate rock types have served to focus deformation, and presumably fluid flow, at various stages during the tectonic evolution of the site. Away from these well understood heterogeneities, the bedrock can be confidently characterized as a relatively homogenous and sparsely fractured rock mass.

Fracture zones, in general, may constitute pathways for groundwater flow and could also be re-activated during future seismic events, and therefore the study of them is important for understanding the suitability of a site for a repository. The geometry of the larger lineaments, nominally 3 km in surface length or greater, are particularly important for determining the optimal layout for the underground repository.

It is also important to note that there is no evidence from any of the data collected to date to suggest that the fractures present at the proposed repository depth beneath the Revell Site have had recent movement (faulting) or have formed in recent geological time.

Most of the drill core shows no evidence of hydrothermal alteration or weathering. Weathering is a process by which rock is modified on exposure to atmospheric agents at or near the surface of the earth. It is only locally present and primarily at depths shallower than 100 m. Deeper in the boreholes, the proportion of moderately altered rock decreases, although it is still observed locally in proximity to zones of increased fracture frequency. Overall, at this point, it is clear that although alteration and weathering are present, their effects are generally weak and these processes have not impacted the overall competence of the bedrock.

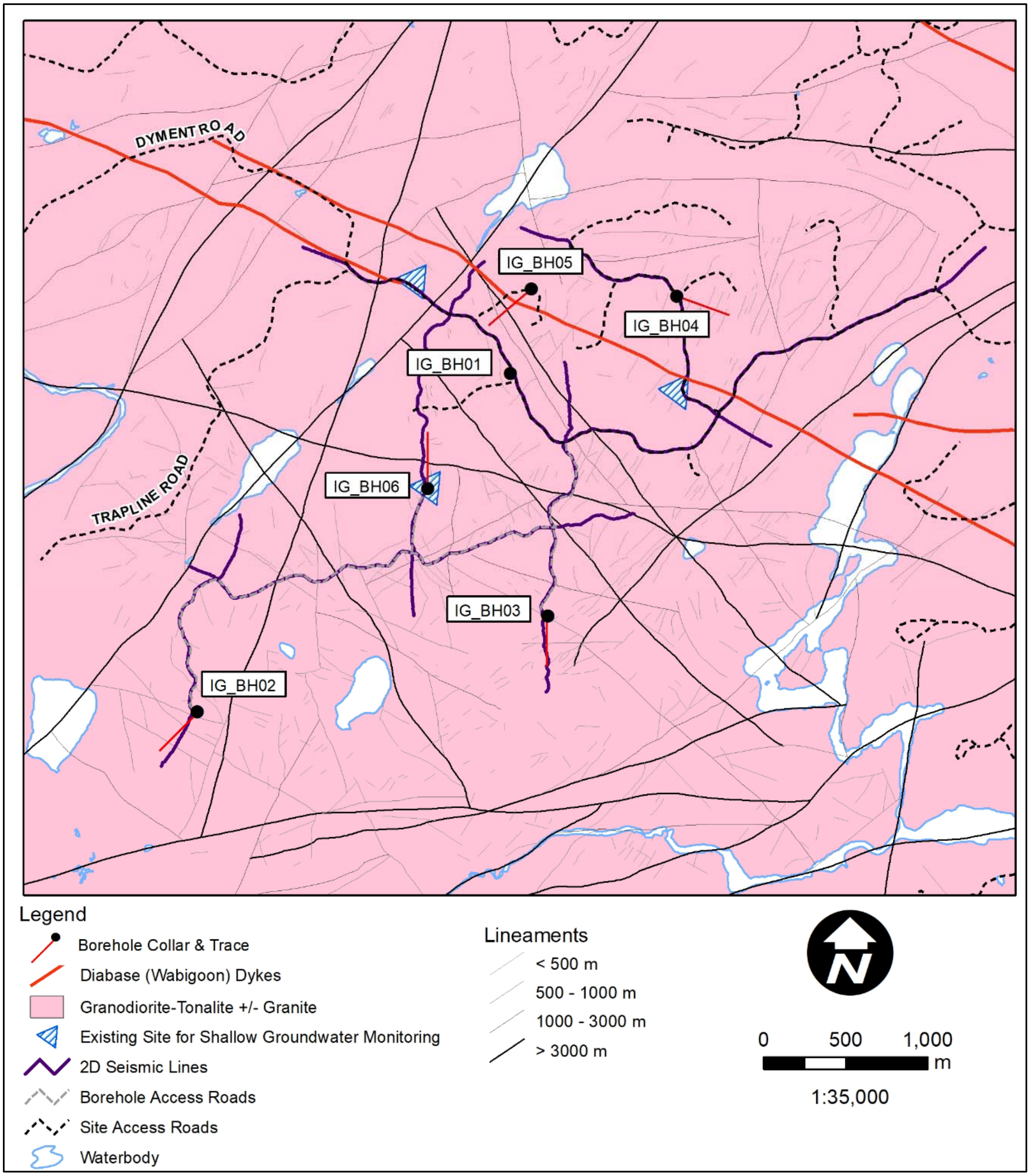

Figure 3.5: Bedrock map of the central part of the Revell Site, also showing deep borehole and shallow groundwater monitoring well locations, 2D seismic acquisition lines, and the surface traces of interpreted lineaments with line styles indicating varying trace lengths.

3.2 Depth and Volume of Competent Rock

The repository depth proposed for the Revell Site must be sufficient to ensure containment and isolation of the used nuclear fuel, including from surface disturbances caused by human activities and natural events (e.g., logging, exploration for natural resources, surface construction, climate change, storms). A depth within a nominal range of 500 to 800 m is considered sufficient, depending on the geological conditions (NWMO 2021a).

Collectively, the geoscientific information, as described in Section 3.1, indicates that the competent granitoid rock extends to at least 1000 m depth, and probably much deeper at the Revell Site. Based further on all information to date, including analyses completed in the past year (described in later sections), the NWMO considers a depth range of 650 m to 800 m as suitable at the Revell Site. The NWMO is presently considering a repository situated at a depth of approximately 750 m. The actual depth will be finalized based on more detailed information on the geology of the site, and results of safety analyses using this additional information.

Further, the regional and site-scale studies conducted to date also indicate that there is sufficient volume of bedrock within the Revell Site to host a deep geological repository. Considering the identification of structural features in the batholith, a deep geological repository can be positioned between the larger-scale structures presently inferred to be fracture zones.

3.3 Composition of Rock, Groundwater and Porewater

The mineralogy of the rock, and the geochemical composition of the groundwater and porewater at repository depth should:

- support the integrity of the multi-barrier system; and
- promote the retardation of radionuclide movement.

From a groundwater/porewater perspective, ensuring that reducing chemical conditions exist at repository depth is important. This is because oxidizing chemical conditions indicate the presence of waters containing dissolved oxygen and recently in contact with the near-surface environment, and therefore would suggest that the geological system is not able to retard radionuclide movement. Oxidizing chemical conditions would also have a negative impact on the engineered barrier system (e.g., copper corrosion).

Total sulphide concentration in the groundwater should also be low in order to maintain the durability of the engineered barrier system. The rock should also have a low concentration of sulphur-bearing minerals.

The mineralogy of the host rock should also have favourable thermal properties in order to ensure good dissipation of residual heat from the used fuel containers. In addition, the rock should have low porosity in order to support the retardation of radionuclide movement. These points are discussed below, except for the thermal properties of the rock which are discussed later in Section 3.5. Overall, the results to date indicate the favourable nature of the mineralogy of the rock, and the geochemical composition of the groundwater and porewater at repository depth, for the Revell Site.

3.3.1 Rock Composition and Porosity

Information on the rock mineralogy (i.e., mineral content) in the Revell Site has been gathered through observations and measurements of the surface geology during geological mapping, and from laboratory analysis of over 100 core samples collected from the six boreholes drilled to date. Data from the boreholes confirm the overall lithological homogeneity of the bedrock with ~95% of the drill core recovered classified as granodiorite-tonalite (e.g., Figure 3.3). The remainder of the recovered core comprises subordinate rock types, including amphibolite sheets and several distinct suites of felsic dykes. The mineralogy of granitoid rock in general, and of the granodiorite-tonalite encountered at the Revell Site, is favourable for construction of a repository. The average model mineral composition of the granodiorite-tonalite includes 44 to 52 % plagioclase, 38 to 40 % quartz, 4 to 9 % biotite, and 1 to 6 % K-feldspar, plus minor trace minerals.

The lithogeochemistry data to date, and logged mineralogy, do not indicate the presence of sulphur-bearing minerals (e.g., sulphides, sulphates) in any appreciable quantities. These low concentrations of sulphur-bearing minerals at the site are not likely to impact the durability of the copper within the engineered barrier system.

The granodiorite-tonalite and amphibolite sheets exhibit low porosity, which is to be expected in these types of rock. The average connected (water-loss) porosity of the granodiorite-tonalite, which represents the porosity within the rock that is connected and filled with fluid, is estimated to be 0.45 volume %. The average total porosity of the granodiorite-tonalite is 1.32 volume %, where the total porosity is considered to be an upper bounding value. In the amphibolite sheets, the average connected and total porosity are estimated to be 0.15 volume % and 1.79 volume %, respectively. Overall, these low porosities will contribute to the retardation of radionuclide movement through the rock.

3.3.2 Groundwater and porewater composition

At the site, groundwater samples were collected where possible from water-bearing fractures intersecting the six boreholes drilled to date. Information on the water composition was also obtained from the minute amount of porewater extracted from rock core samples collected at different depths, as well as from on-going sampling of sections within four of the boreholes. The composition of the groundwater samples, and the porewater from core samples, show trends with depth that are consistent with expectations for a Canadian Shield environment. Fresh (non-saline) water conditions are encountered in a shallow hydrogeochemical zone (less than about 300 m depth) dominated by $Ca\text{-}HCO_3^{2-}$. A deep hydrogeochemical zone encountered approximately 600 to 650 m below ground surface, equivalent to an elevation of approximately -150 to -200 metres above sea level, is characterized by a higher salinity Ca-Na-Cl ($-HCO_3^{2-}$) composition, and a steadily increasing salinity toward the base of all six boreholes.

To illustrate this stratification, Figure 3.6 includes a summary of chloride concentrations from water samples analysed to date. The upper boundary of the intervening transition zone varies somewhat in depth, dependent on the borehole locations. However, the increase in salinity marking the transition into the deep hydrogeochemical zone is consistent in depth across all boreholes. This increase in salinity with depth is a function of the reduced influence of fractures as a connected flow path network at deeper levels in the bedrock beneath the Revell Site. The presence of increasing salinity, as shown in Park et al. (2009), can indicate a stable hydrogeochemical environment at depth.

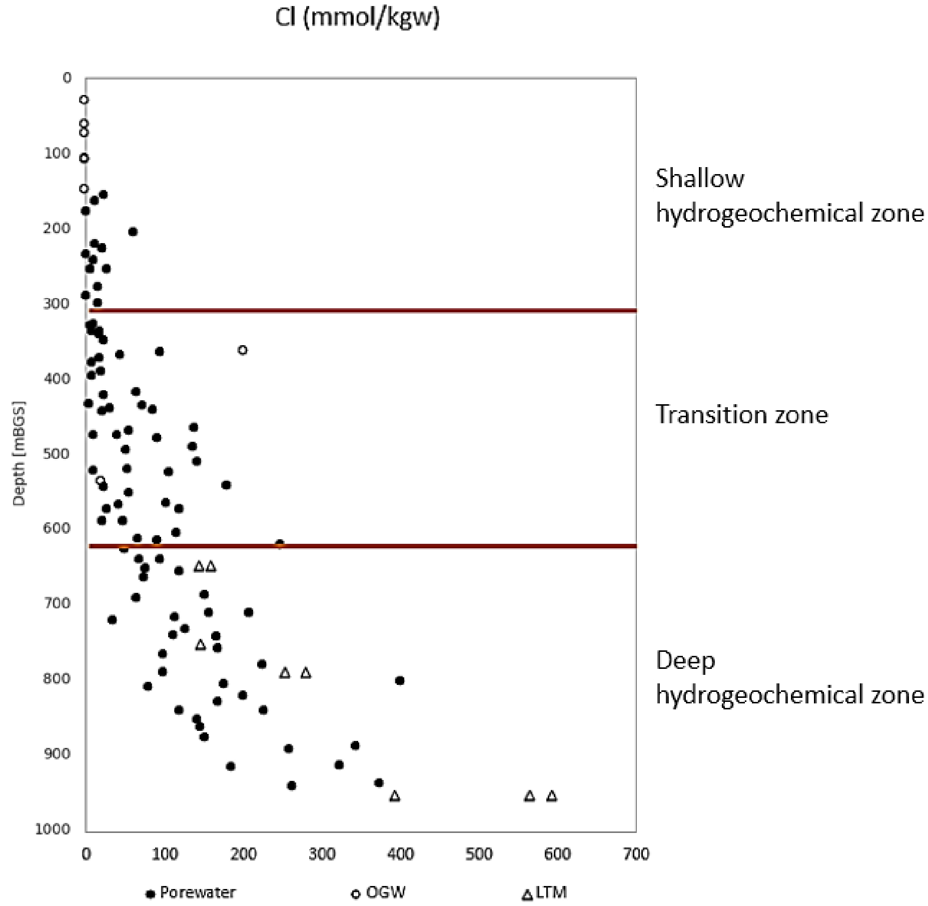

Figure 3.6: Summary of results from opportunistic groundwater (OGW), porewater, and long-term monitoring (LTM) groundwater samples. These results illustrate a trend of steadily increasing salinity (represented here by chloride) with increasing depth beneath the Revell Site. Zone boundaries are approximate.

The results indicate that the shallow and deep hydrogeochemical zones contain fluids with different major ion chemistry and isotopic composition and have no direct connection. Between the shallow and deep hydrogeochemical zones is a broad transition zone (Figure 3.6). The chemistry of the deep hydrogeochemical zone is consistent with very old water.

Although measurements to date are limited, there is no evidence that glacial meltwater has penetrated into the deep hydrogeochemical zone. In addition, from groundwater samples collected to date for noble gas characterization, helium concentrations and isotopes in the deep hydrogeochemical zone, indicate the waters at such depths are more than one million years old. These results are favourable for providing confidence that a repository located within the deep hydrogeochemical zone will remain isolated from the near-surface, providing protection for shallow groundwater resources and the biosphere.

In addition, the results from the groundwater and porewater samples that have been analyzed to-date support the presence of reducing conditions (i.e., dissolved oxygen is not present) at depths below 600 to 650 m (i.e., within the deep hydrogeochemical zone), which are favorable for durability of the container and the fuel barrier.

For all groundwater samples collected to-date, the total dissolved sulphide concentrations were very low, below the method detection limit of 0.02 mg/L. These low sulphide concentrations are not likely to impact the durability of the copper within the engineered barrier system.

3.3.3 Summary

There are no indications from the analyses to date that the properties of the rock or water chemistry at the Revell Site will adversely impact the repository multi-barrier system. In addition, the properties of the rock and water chemistry will promote the retardation of radionuclide movement.

3.4 Hydrogeological Regime

To slow down the movement of any radionuclide and ensure the isolation of the used fuel from the environment, the hydrogeological regime within the host rock should exhibit low rates of mass transport at repository depth, i.e., the properties of the host rock should be such that if a radionuclide were to be released, its transport through the groundwater would be so slow that radionuclides would have time to decay to insignificant levels before reaching the surface.

The ability of water to move through rock is referred to as the rock's **hydraulic conductivity** or the related properties **permeability** or **transmissivity**. Throughout the remainder of this section, the term transmissivity will be used, which is more appropriate for the crystalline rock at the Revell Site. The larger the value of transmissivity, the more easily water can move through the rock.

The ability of water to move through the rock was observed at site directly through groundwater sampling collected during drilling and during long-term monitoring, and indirectly through downhole hydraulic packer testing and geophysical logging.

First, during the drilling of the six boreholes at the Revell Site, groundwater samples were collected when possible. For groundwater samples to be collected while drilling, appreciable groundwater must be able to flow into the borehole. This is an indirect indication of groundwater velocities of the host rock at subsurface. For the six boreholes drilled to date, there were only five instances below 200 m depth where groundwater was able to flow into the borehole at levels sufficient to collect groundwater samples during drilling.

Second, additional groundwater samples were successfully collected as part of long-term monitoring in four of the deep boreholes. As discussed in Section 3.3, and illustrated in Figure 3.6, the composition of these additional samples supports the understanding that the increase in salinity with depth is a function of the reduced influence of the overall role of fractures as a connected flow path network at deeper levels.

Third, the primary source of information on the host rock's transmissivity is hydraulic packer testing in the deep boreholes. Packer testing was conducted in all six boreholes, for 20 to 30 intervals, at different depths. Additional information on groundwater flow was also obtained from other borehole testing (i.e., geophysical logging) and from long-term pressure monitoring at discrete intervals along some of the deep boreholes.

One of the key reasons for undertaking these tests is to investigate variation in transmissivity with depth at the Revell Site. Researchers at the University of Waterloo (Snowdon et al. 2021) compiled data from seven research sites across the Canadian Shield, including batholiths and other rock units. Their analysis included categorization of the hydraulic testing data into Equivalent Porous Medium (EPM) rock mass measurement or fracture measurement data on the basis of observed hydraulically conductive features. The term EPM rock mass refers to a volume of rock consisting of rock matrix and brittle structures with no observed flowing conditions. The results indicate a general pattern of decreasing transmissivity with depth in the Canadian Shield for both EPM rock mass and fracture data.

At the potential repository depth of around 750 m in the Revell Site, the transmissivity values estimated for the rock mass from the six deep boreholes have a median value between 10^{-13} and 10^{-10} m^2/s (Figure 3.7), decreasing with depth. These site-specific data are within the expected range of, or slightly lower than, the broader Canadian Shield data in Snowdon et al. (2021). Overall, transmissivity values estimated for the EPM rock mass at the Revell Site indicate low groundwater velocities. For comparison, the transmissivity of a 20 m thick layer of pure sand, which is the same as the width of the packer testing interval used for the Revell Site, ranges from 2×10^{-5} to 2×10^{-1} m^2/s. In other words, the estimated rock mass transmissivities at the Revell Site are about a million times smaller than that of sand.

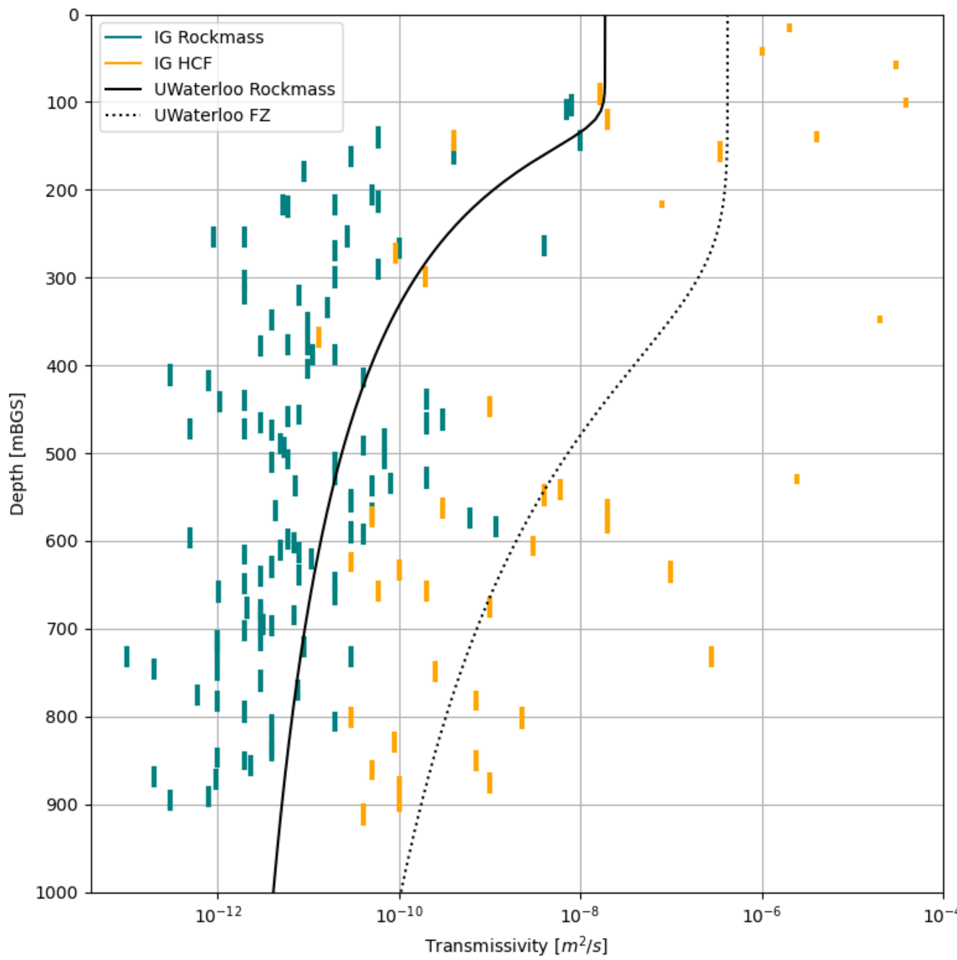

Figure 3.7: Results from borehole hydraulic packer testing, reported as transmissivities (m^2/s). Results are categorized as rock mass (IG Rockmass) or hydraulically-conductive features (IG HCF). Average rockmass and fracture zone (FZ) transmissivity from the University of Waterloo database (Snowdon et al. 2021) are also shown.

In tested borehole intervals that were interpreted to represent flowing fractures, the transmissivity ranged between 10^{-12} and 10^{-5} m^2/s. In these intervals the fracture intensity was usually increased and, commonly, there was presence of at least one broken (non-cohesive), sub-horizontal to gently-inclined fracture close to or along the contact between the granodiorite-tonalite and a subordinate rock occurrence, such as amphibolite. These structures have been identified as pathways for groundwater flow.

Following the completion of drilling and downhole testing in three boreholes, multilevel monitoring systems were installed. These systems permit long-term measurement of pressures and collection of groundwater samples from intervals in the borehole. Pressure distributions in these boreholes indicate the presence of increasing groundwater fluid density at depths below ~600 m at the Revell Site, suggesting increasing salinity in the water, consistent with the hydrogeochemistry results discussed in Section 3.3. The presence of increasing salinity, as shown in Park et al. (2009), can indicate a hydrogeologically stable environment at depth.

The available information provides confidence that the hydrogeological regime at depth at the Revell Site likely has low rates of mass transport in areas of the rock mass away from potentially flowing fracture zones.

3.5 Bedrock Stresses, and Geomechanical and Thermal Properties

The host rock must be strong enough to withstand natural stresses as well as stress changes induced by the presence of the repository. In general, granitoid rocks are known to be strong; however, the strength of the rock at the Revell Site remains to be confirmed. This requires measuring the rock mechanical properties and considering both natural stresses in the rock as well as those induced by the repository constructions, and thermal stresses caused by the heat generated from the used fuel.

3.5.1 Bedrock Stresses

Bedrock stresses result from the natural forces acting on the bedrock. Understanding the magnitude and direction of stresses in the bedrock is an important input for the design of the repository, specifically when aligning the orientation of the rooms and panels of the repository to optimize stability. At this stage of the site selection process, no direct stress measurement activities have been undertaken for the Revell Site.

Based on a compilation of available stress measurement data, Yong and Maloney (2015) developed a general model of the variable stress state in the upper 1,500 m of the Canadian Shield. They identified a shallow stress-relaxed zone from the ground surface down to a depth of 300 m, a transition zone from 300 to 600 m, and a stable stress zone below 600 m. They also reported magnitudes and orientations for the three principal stresses. Preliminary repository layouts are being developed for the Revell Site considering this information; during detailed site characterization, site-specific stress measurements will be taken to refine the repository layout.

At this stage, information from borehole wall damage can help define bounding limits for the principal stress ratios and orientations. Borehole wall damage refers to locations along a borehole where parts of the rock around the cylindrical hole have broken off after the core was removed. The location and magnitude of such damage can be used to infer information on the local stress fields.

At the Revell Site, several borehole breakouts were identified in four out of the six boreholes. These breakouts occurred at depths ranging between approximately 600 m and 950 m. This is not unexpected at depth for bedrock in the Canadian Shield. The preliminary interpretation of these data indicates that the orientation of the maximum horizontal stress in the Revell Site follows the general East-West to Northeast-Southwest trend in the Canadian Shield reported by Yong and Maloney (2015).

The Revell Site borehole breakouts occur within the same depth range as the undisturbed stress zone defined by Yong and Maloney (2015), i.e., below 600 m. It is therefore reasonable to infer that a similar undisturbed stress zone occurs below 600 m at the Revell Site. Furthermore, the near alignment of the undisturbed stress zone and the deep hydrogeochemical zone beneath the site, which as mentioned in Section 3.4 begins at about 600 – 650 metres below ground surface, provides strong evidence that the bedrock below this depth is isolated from near surface geological perturbations. In summary, the Yong and Maloney (2015) Canadian Shield stress zonation model provides a reasonable analogue for bounding the likely in situ stress conditions beneath the Revell Site, and that it is suitable to use this stress model until it can be tested with site-specific measurements in future investigations.

3.5.2 Rock Mechanical Properties

Rock strength of intact samples is mainly determined based on laboratory testing of intact core samples of granodiorite-tonalite, and limited laboratory testing of subordinate rock types present in small amounts such as amphibolite sheets. Direct shear tests are also underway to determine shear strength properties of rock fractures mainly from fractured granodiorite-tonalite samples.

In each borehole, field strength index measurements by hammer test were made while breaking the core for sampling and for fitting core into the core boxes. In many instances, intact sections of core three metres in length, the same length as the core barrel, were recovered during drilling (e.g., Figure 3.8). Based on the field strength test results, the rock at the Revell Site can generally be classified as very strong.

Based on the experimental data collected to date, average rock mechanics properties of the granodiorite-tonalite included an average density of 2.66 g/cm^3 and an average uniaxial compressive strength (UCS) of 225 MPa (e.g., Golder 2022b). The subordinate rock types had mechanical properties within approximately the same order of magnitude as granodiorite-tonalite; for example, samples of amphibolite sheets showed an average density of 2.96 g/cm^3 and an average uniaxial compressive strength of 204 MPa. These preliminary rock mechanics properties of intact rock samples in the Revell batholith confirm that the rock has high strength, typical of granitoid rocks. For example, granite-granodiorite from the Forsmark site in Sweden has an average UCS of 226 MPa (SKB 2008). The values for Revell granodiorite-tonalite are also similar to those of similar rock types elsewhere in the northwestern Ontario (e.g., Stone et al. 1989).

Figure 3.8: Example of an intact, three-metre long, section of drill core displaying the low fracture frequency typical of the high strength granodiorite-tonalite of the Revell Site.

3.5.3 Rock Mass Properties

In addition to determining the mechanical properties at the core sample scale, it is also important to assess the structural integrity of the rock mass, which refers to a larger scale representation of the bedrock, considering the presence of fractures, weathering and alteration. A significant presence of these features could have a negative effect on the integrity of the rock mass. Data on rock mass properties were obtained mostly from core logging and downhole testing (i.e., geophysical logging and hydraulic testing).

Rock mass properties are similar for the bedrock intersected by all boreholes. This result is consistent with the relative homogeneity of the bedrock beneath the Revell Site. As noted above in Section 3.3, the degree of weathering and alteration is low and does not appear to have any significant role in controlling rock mass properties, and may only affect properties locally (e.g., near fracture zones, including fracture zones that are hydraulically conductive).

The rock-quality designation (RQD) is a quantitative index of rock quality based on the total cumulative length of core recovered in lengths greater than 10 cm (4 inches), as measured from midpoint to midpoint of natural broken discontinuities (i.e., fractures), ‘Good’ quality rock has an RQD of more than 75%, and ‘excellent’ quality rock has an RQD of more than 90%, whereas poor quality rock has an RQD of less than 50%.

At the Revell Site, the rock is considered to be excellent rock quality, averaging 98 % RQD or greater for all six boreholes. Lower RQD values are predominantly encountered in the shallow subsurface, and in proximity to some occurrences of the subordinate rocks that represent a small amount, by volume, of the rock mass. In addition, typical broken fracture spacing observed from the first three boreholes is generally lower (from less than 1 m to 3 m) in the upper section of the boreholes to approximately 100 m depth; at greater depths, the typical broken fracture spacing increases to greater than 3 m. Fracture frequency tends to increase in sections containing subordinate rock types and in intervals confidently linked to surface lineaments (i.e., fracture zones).

Overall, the analyses indicate that the rock mass properties in the Revell Site are typical of sparsely fractured, high-quality, strong, crystalline rocks. The low level of both alteration and weathering, which could impact rock strength, the low fracture frequency per metre, and high RQD are characteristic of the bedrock encountered in all six boreholes. The overall homogeneity of the bedrock provides confidence that these rock mass properties are indicative of the bedrock across the site.

3.5.4 Thermal Properties

The host rock should be able to conduct away the heat generated from the used fuel, and to withstand thermal stresses induced by this heat, without significant structural deformation or fracturing that could compromise the containment and isolation functions of the repository.

Current thermal property data are based on laboratory testing of core samples of granodiorite-tonalite and limited testing on subordinate rock types, such as amphibolite sheets, from the first three boreholes. Testing of thermal properties on core samples from other boreholes is ongoing. The average thermal conductivity of the granodiorite-tonalite at room temperature was measured at 3.34 W/m.K. The average thermal conductivity of the amphibolite sheets at room temperature was measured at 2.64 W/m.K. These results are within the expected range of values based on the mineralogy of these rock types.

Based on the available data, the thermal properties of intact rock in the Revell Site are similar to those of equivalent rock types elsewhere in northwestern Ontario. The thermal, and geomechanical, properties of the Revell Site granodiorite-tonalite are comparable to those of the Lac du Bonnet granite in Manitoba (e.g., Drury and Lewis, 1983), and also comparable to rock from the Forsmark repository site in Sweden (e.g., SKB 2007), and the Olkiluoto repository site in Finland (e.g., Åkesson 2012).

Furthermore, information on the geothermal gradient in the Revell Site has been collected from downhole testing data obtained in the deep boreholes. Data from the first three boreholes shows a natural geothermal gradient of 9.9°C/km, which is within the range expected for the Canadian Shield, including the Lac du Bonnet batholith (Drury and Lewis 1983).

Based on this information and preliminary models (e.g. Guo 2023), the bedrock underlying the Revell Site is capable of removing the decay heat from the fuel and withstanding thermal stresses induced by the repository.

3.5.5 Summary

The rocks of the Revell batholith are similar to those of other crystalline rocks of the Canadian Shield, and to those of other international waste management programs. They are relatively predictable and not unusual in their mechanical and thermal behaviour, enabling them to be confidently characterized and modelled. It can be concluded with confidence, with uncertainty that is acceptable at this stage of site characterization, that the strong granitoid rocks that represent the majority of the bedrock beneath the Revell Site are capable of removing the decay heat from the fuel, and withstanding the natural stresses and thermal stresses induced by a repository.

4. LONG-TERM GEOLOGICAL STABILITY OF THE SITE

The site must provide long-term geological stability for the repository. In particular, the repository should not be unacceptably affected by future geological processes and climate changes, including earthquakes and glacial cycles.

The ability of a site to provide this stability is assessed through the following site evaluation factors:

1. Seismicity: Seismic activity (i.e., earthquakes) at the site should not adversely impact the integrity and safety of the repository during operation and in the very long term.

2. Land uplift, subsidence, and erosion: The expected rates of land uplift, subsidence and erosion at the site should not adversely impact the repository.

3. Future glacial cycles: The evolution of the conditions at repository depth during future climate change such as glacial cycles should not have a detrimental impact on the repository.

4. Distance from geological features: The repository should be located at a sufficient distance from geological features such as zones of deformation or faults that could be potentially reactivated in the future.

Each of these are discussed in the subsections below.

4.1 Seismicity

The Revell Site is located in a stable, seismically quiet setting in the Canadian Shield at the heart of the North American continent, away from tectonic plate boundaries. It is considered a **craton**, which is a large stable block of the earth’s crust forming the nucleus of a continent.

The Canadian government has maintained a network of monitoring stations that record the location and magnitude of seismic events across the country. In northwestern Ontario, these have been supplemented by the NWMO with additional stations to improve the data coverage and accuracy (e.g., Ackerley et al. 2021). Figure 4.1 shows seismic activity for central Canada and part of northern United States, as recorded by the Canadian Hazard Information Service (CHIS), between 1980 and 2023. Earthquakes are measured using the Nuttli Scale (m_N), which represents a modern refinement of the older Richter scale.

To date, in the CHIS dataset, there have not been any earthquakes above magnitude 3 m_N, a magnitude typically felt by most humans, occurring within 50 km from the Revell Site. The majority of the seismic events recorded in the vicinity of the site were caused by human activity, such as from blasting activities at mines.

A network of nine microseismic monitoring stations was installed by the NWMO around the Revell Site in 2021. These nine stations provide increased ability to identify and locate smaller earthquakes within a 50 km radius of the site. Microseismic data, presented in Figure 4.2 in local Richter Magnitude (ML), were collected during 2022 as part of this recently installed microseismic monitoring network (Nanometrics 2023). Local Richter Magnitude is the standard reporting datum for micro seismicity and is best used for “Local” earthquakes with epicenters located up to 600 km from seismic stations.

To date, in the NWMO microseismic dataset, there have not been any earthquakes above magnitude 2 ML. The closest recorded was 0.5 ML in the north part of the Revell batholith.

Microseismic monitoring will continue to record seismic events to aid in identifying the presence of any active faults in the regional area surrounding the Revell Site. Monitoring of small magnitude events (magnitude 3 ML and lower) provides information on the overall seismicity and geological structure of the local region surrounding the Revell Site. Ground vibrations associated with these small magnitude events are below the threshold considered to be able to cause structural damage to buildings.

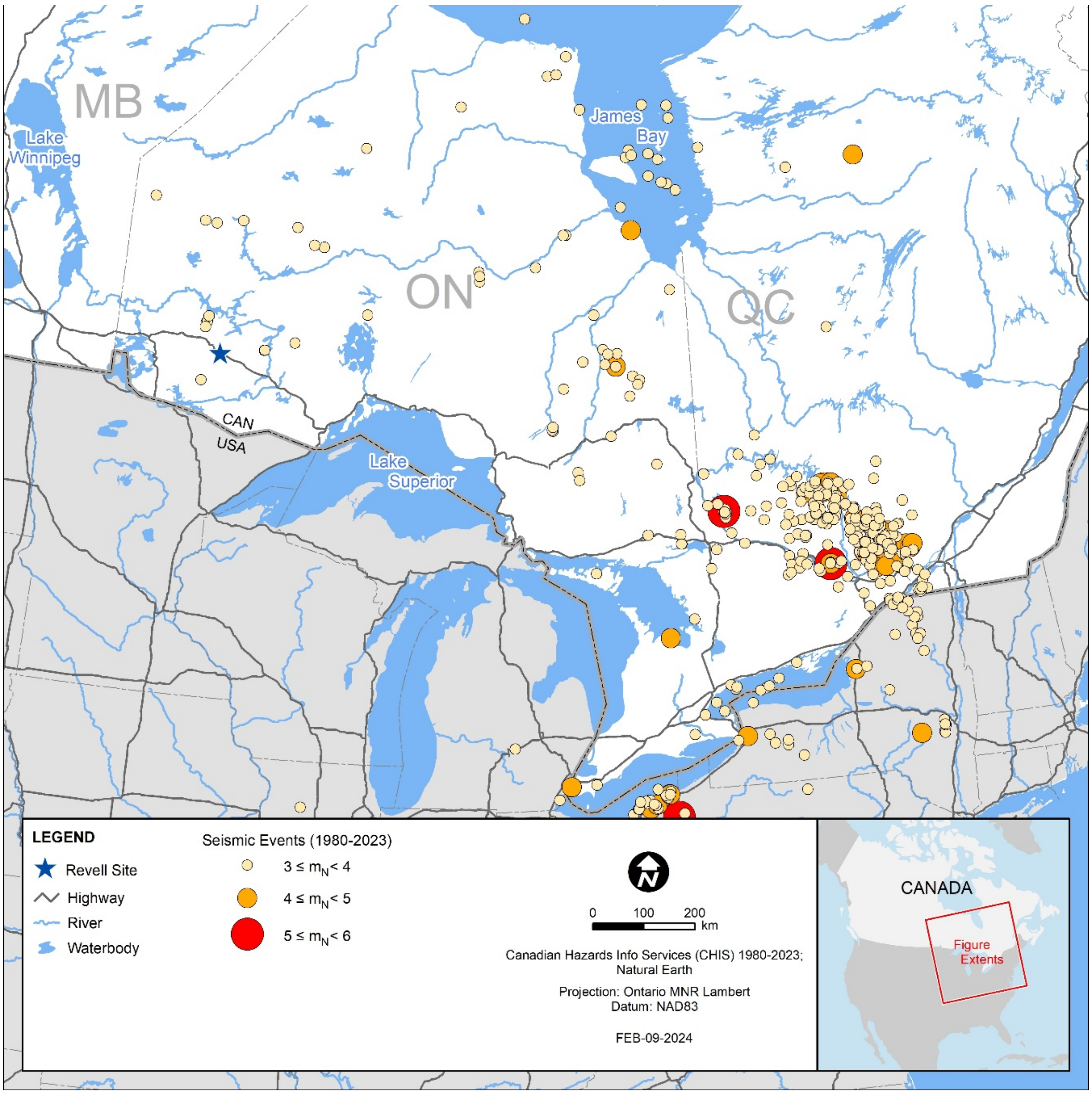

Figure 4.1: Earthquakes with Nuttli magnitude (m_N) greater or equal to 3 recorded in central Canada and part of northern United States, 1980–2023.

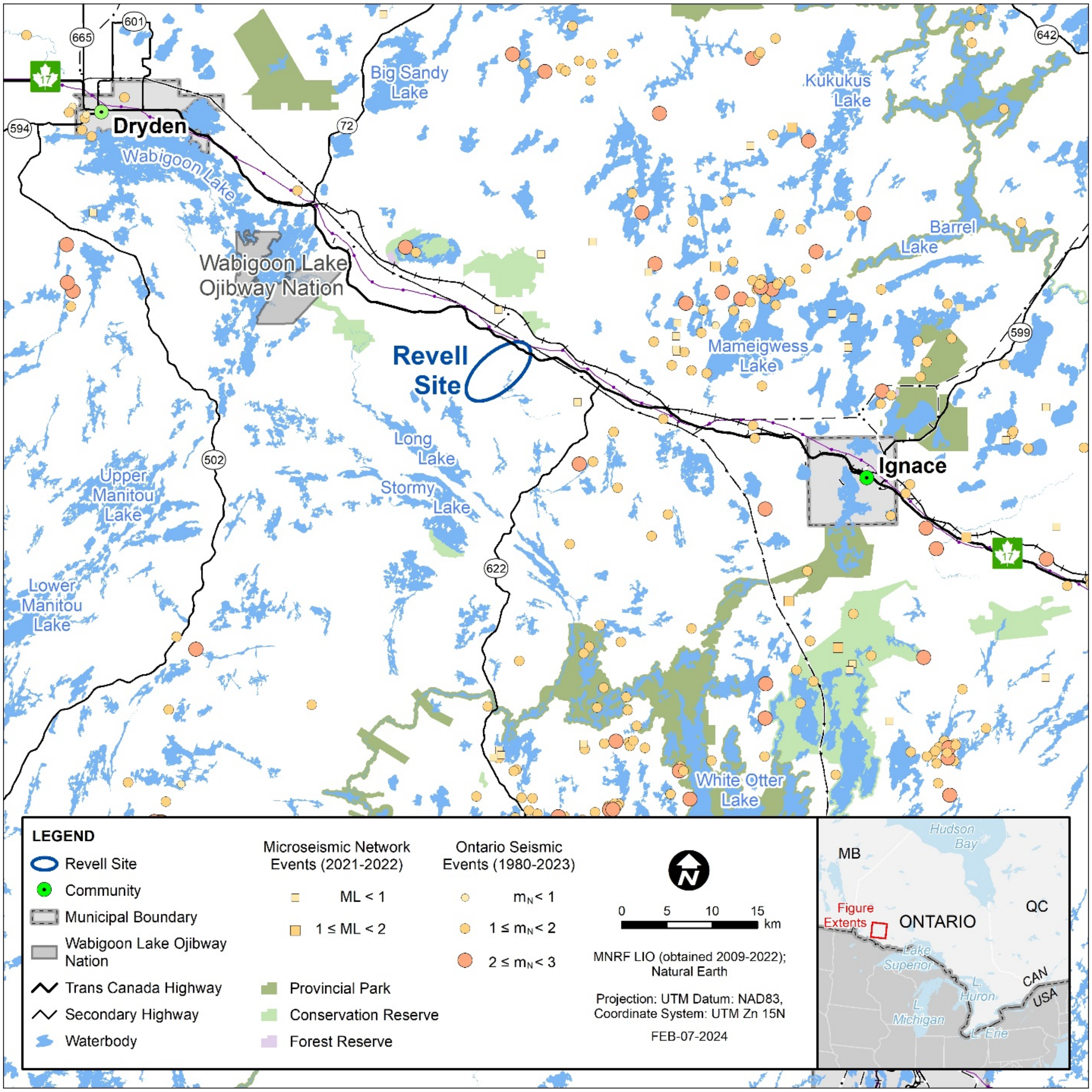

Figure 4.2: All seismic activity recorded around the Revell Site compiled from CHIS and from NWMO's microseismic network. Activity levels less than magnitude 3 are generally too low to be noticed by people, but can provide geological information about bedrock structure.

4.2 Land uplift, subsidence and erosion

To ensure the containment and isolation functions of the repository continue in the future, it is important to understand potential changes in the repository depth below ground surface.

The Canadian Shield has remained tectonically stable throughout much of northwestern Ontario since approximately one billion years ago, except for localized rifting approximately 600 million years ago in eastern Ontario (Percival and Easton 2007). This area of the Shield was eroded to a nearly flat surface of regional extent prior to the onset of multiple cycles of deposition and erosion of sedimentary rocks, and associated vertical and lateral crustal motion, over the last approximately 500 million years.

On a million-year timeframe, the main geological process that could possibly impact the stability of a repository at the Revell Site is expected to be in relation to future glacial cycles (Robin et al. 2020). These glacial cycles, expected to occur every 120,000 years, can cause the land to depress (subside), uplift, erode, or to become covered with glacial deposits, which can in turn affect the depth to the repository.

During glaciation, the bedrock is depressed by the weight of the icesheet. Afterwards the bedrock slowly rises back. The bedrock in the Ignace area is presently uplifting at 3-5 mm per year, as the continental crust slowly recovers from the last ice age (Sella et al. 2007). This process is slow, and occurring relatively uniformly around the Revell Site area, so by itself does not affect repository depth.

More significant is the possibility of glacial erosion. A recent study by Naylor et al. (2021), suggests an erosion rate of approximately 35 metres per million years in this portion of the Canadian Shield, which is comparable to previous estimates (Bell and Laine 1985). Hall et al. (2019) estimate a similar range of between 2 and 43 m of glacial erosion over the next million years for a crystalline bedrock study site in Sweden. Ongoing studies will further refine rates of erosion for the Canadian Shield in closer proximity to the Revell Site.

There is currently no indication that the location where the Revell Site is located will experience extreme rates of erosion, uplift, or subsidence that would significantly perturb the deep geosphere over the next million years. Studies of bedrock erosion indicate that this type of process will be very unlikely to impact repository safety.

4.3 Future glacial cycles

The climate is expected to change in the future. In the near term, the climate will be influenced by global warming. This is expected to cause changes in weather in northwestern Ontario; the nature of the changes is estimated in Golder (2020). These changes will be important to people and to the surface environment but are unlikely to significantly affect conditions at the repository depth, several hundred metres below surface.

In the future, 50,000 years or more, ice age conditions are expected to return. These conditions have occurred approximately every 120,000 years for the past million years, largely due to the nature of the earth's orbit around the sun. The most recent modelling work suggests that in proximity to the Revell Site, the last ice age started about 120,000 years ago with the onset of permafrost development ahead of the advancing ice sheet, and ended about 10,000 years ago, when the ice retreated out of Ontario towards northern Canada (Figure 4.3).

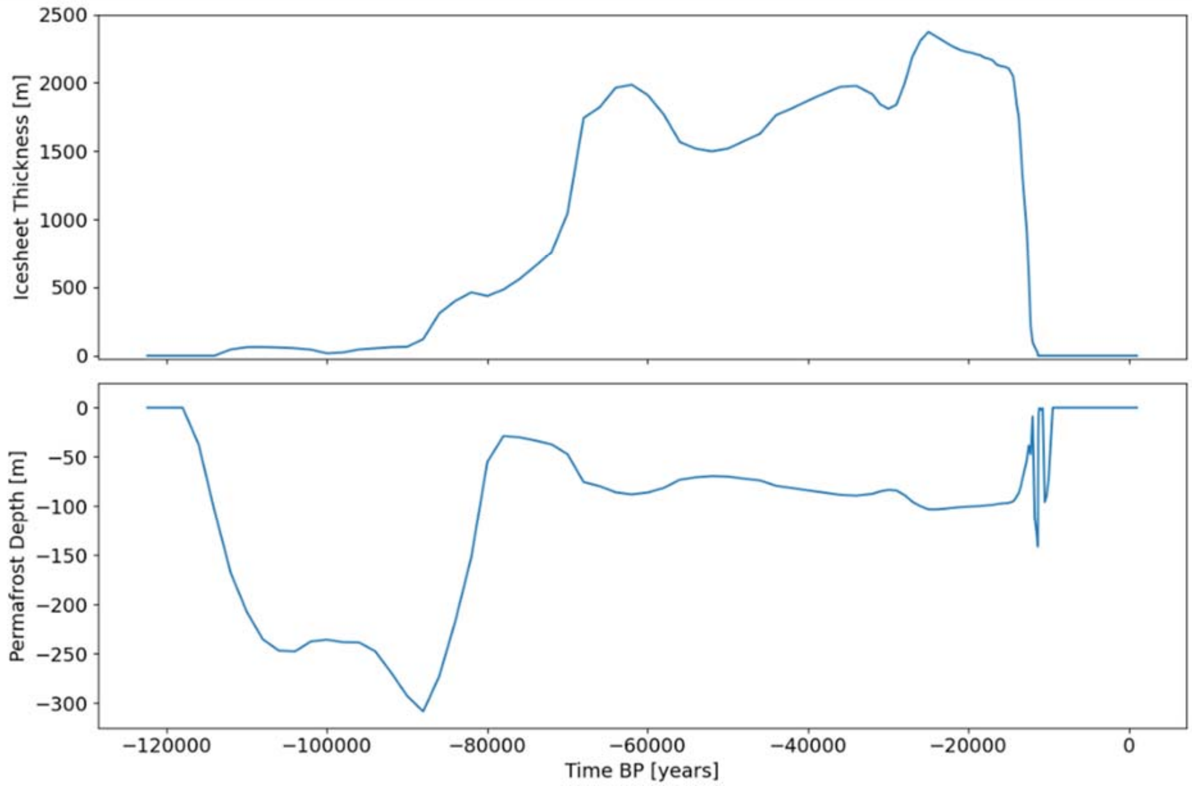

Figure 4.3: Evolution of ice sheet thickness (top) and permafrost thickness (bottom) for the region surrounding the Revell Site since 120,000 years before present (BP) based on the University of Toronto Glacial System Model (based on Stuhne and Peltier 2023).

The model results also suggest that in proximity to the Revell Site the last ice sheet reached a maximum thickness of almost 2.5 km, and that permafrost attained a maximum depth of approximately 300 m below ground surface (Figure 4.3). These results provide site-specific refinement to previous modelling predictions that suggested there can be up to a 2.5 km thick ice sheet over Ontario (Peltier 2011; Stuhne and Peltier 2015, 2016).

In the long-term, one of the key aspects to consider for the stability of the repository is the effect that future glaciations could have on the subsurface. It is specifically important to demonstrate that oxygenated fresh water from future ice sheets will not penetrate to repository depth; the presence of this water would compromise the integrity of the repository, in part through enhancing corrosion of the used fuel containers, and potentially, erosion of the bentonite buffer.

Currently, the best indication of the impact of future glaciations on the Revell Site is evidence of how the site performed during past glaciations. Based on available data, glaciations have had minimal impact on the rocks and fluids (water and gases) at repository depth at the Revell Site. As noted in Section 3.3, there is no evidence at the site that glacial meltwater has penetrated to repository depth. The trends in both the groundwater and porewater chemistry profiles with depth in the boreholes drilled to-date indicate that the increased salinity conditions at the potential repository depth of about 750 m are distinct from the freshwater conditions identified in the upper 300 m of bedrock, as discussed in Section 3.3 and shown in Figure 3.6. The site-specific results correlate well with the model estimate of 300 m for the maximum depth of penetration of permafrost in the Revell Site area during the last glacial cycle (Figure 4.3).

Future ice sheets should also not have a negative impact on the geomechanical stability of the repository. The weight of the thick ice sheets, and the changing stress conditions and bedrock surface topography during advance and retreat of the ice, need to be taken into consideration in the design of the repository. For instance, the used fuel containers (Section 7) are designed to withstand the long-term repository loads including future ice sheets over the repository. A key component of the repository design is sealing for decommissioning and the post-closure phase; specifically, all placement rooms with containers are filled with bentonite clay to aid in stability under these loads. Similarly, all other underground openings and shafts (e.g., access tunnels, services area, etc.) will be fully backfilled and/or sealed.

As noted in Section 3.5, although no site-specific in situ stress measurements have been collected to date, there is sufficient site-specific and analogue information to infer a preliminary stress model that includes a stress-relaxed domain down to 300 m and a deep stable stress domain below 600 m at the Revell Site. The coincidence between these domains and the shallow and deep hydrogeochemical zones beneath the site suggests that the deep stable stress domain is present because it has remained isolated from perturbations, including glaciation.

In summary, multiple lines of evidence suggest that future climate change scenarios such as glacial cycles will impact the upper approximately 300 m of bedrock at the Revell Site but will have virtually no impact on the bedrock at the potential repository depth of 750 m. At this depth, bedrock stresses and hydrogeochemical conditions are expected to remain stable during future glacial cycles.

4.4 Distance from geological features

The repository should be located at a sufficient distance from geological features such as major faults that could be potentially reactivated in the future, possibly through post-glacial earthquakes. These important geological features include regional structures that are up to hundreds of kilometres in length. These geological features are interpreted to have formed during the Archean stage of amalgamation of the Canadian Shield about 2.7 billion years ago.

The Revell Site was selected as a candidate site, in part, because it is located at a sufficient distance from these regional geological features. The regional scale geological features are typically east-west to northeast striking, with the closest mapped structure being approximately 10 km to the southwest from the site scale model boundary and located within the Bending Lake Greenstone Belt.

In addition, the on-going microseismic monitoring has not identified any seismic events occurring within the boundary of the Revell site. As noted in Section 4.1 above, a small 0.5 ML event located near the northern boundary of the Revell batholith is the nearest recorded event. As noted above, microseismic monitoring will continue to record seismic events to aid in identifying the presence of any active faults in the regional area surrounding the Revell Site, which would then be accounted for in the repository placement.

The retreat of future ice sheets could lead to post-glacial earthquakes. Since the repository would have been backfilled and sealed and be resilient to seismic events, the main potential impact would be through the extension of permeable fracture pathways in the geosphere. This is addressed through repository placement to avoid the larger existing lineaments as noted in Section 7.2.

5. FUTURE HUMAN INTRUSION

An objective of a deep geological repository is to minimize the risk of inadvertent future human intrusion into the used fuel waste. Therefore, the site should be selected to minimize the potential for disruption by future human activities, such as inadvertently drilling into the repository.

To minimize the likelihood of inadvertent future human intrusion, the repository:

1. Should not be located within rock units containing economically exploitable natural resources such as gas/oil, coal, minerals and other valuable commodities as known today.

2. Should not be located within geological units containing groundwater resources at repository depth that could be used for drinking, agriculture or industrial uses.

Each of these requirements is discussed in the subsections below.

5.1 Economically exploitable natural resources

The Revell Site is in a crystalline rock environment in the Canadian Shield. Petroleum (gas/oil) and coal resources are not encountered in crystalline environments. Economically exploitable natural resources in the Canadian Shield are mainly limited to mineral resources.

Generally speaking, relatively undeformed granitoid intrusions like the Revell batholith do not contain economically exploitable mineral resources. Mineral resources are more often found in greenstone belts, like the Raleigh Lake and Bending Lake greenstone belts that surround the Revell batholith (see Section 3.1). In greenstone belt settings, the high degree of fracturing has allowed for the flow of hydrothermal fluids, which often generate ore deposits.

Publicly available datasets from the Ontario Geological Survey provide information on the historic to recent exploration, sampling, and geophysical work completed in the vicinity of the Revell Site. As shown in Figure 5.1, current mining activities are limited to the greenstone belts, with some mining claims straddling the margins of the Revell batholith. An open-pit mine has been proposed to extract iron ore concentrated within the iron formation located to the south of the Revell batholith (Figure 5.1). The mining claims that extend across the southern part of the Revell batholith include areas identified as possible waste-rock pile locations for this proposed open-pit operation; they are not an indication of mineral potential of the Revell batholith.

Overall, no known economically exploitable mineral resources have been previously found in the Revell Site (e.g., Golder 2017). No known mineral mining activities have occurred at this location, and no indications of mineral resource potential have been identified in the data collected to date, including geological mapping data, airborne geophysical surveys and data from the six boreholes drilled.

The mineral resource potential of the bedrock underlying the Revell Site was assessed through examination of lithogeochemical data from the first three boreholes (Alba Geosolutions and Consulting 2024). Based on comparison of this data against typical ore grades for a range of metallic elements, and in comparison to adjacent granitoid rocks of similar age and composition, this study concluded that the Revell Site has extremely low mineral potential. Basically, the Revell Site rock has a common granitoid composition with no evidence for useful minerals.

The Revell batholith, due to its lithological homogeneity and low fracture frequency, has been identified as favourable for the extraction of building stone (e.g., Storey 1986). However, given the size of the batholith, there is no reason such activities would occur at the Revell Site nor that they would need to go to repository depths.

Taken together, these findings indicate no known economically exploitable mineral resources have been identified at or near the proposed repository volume at the Revell Site.

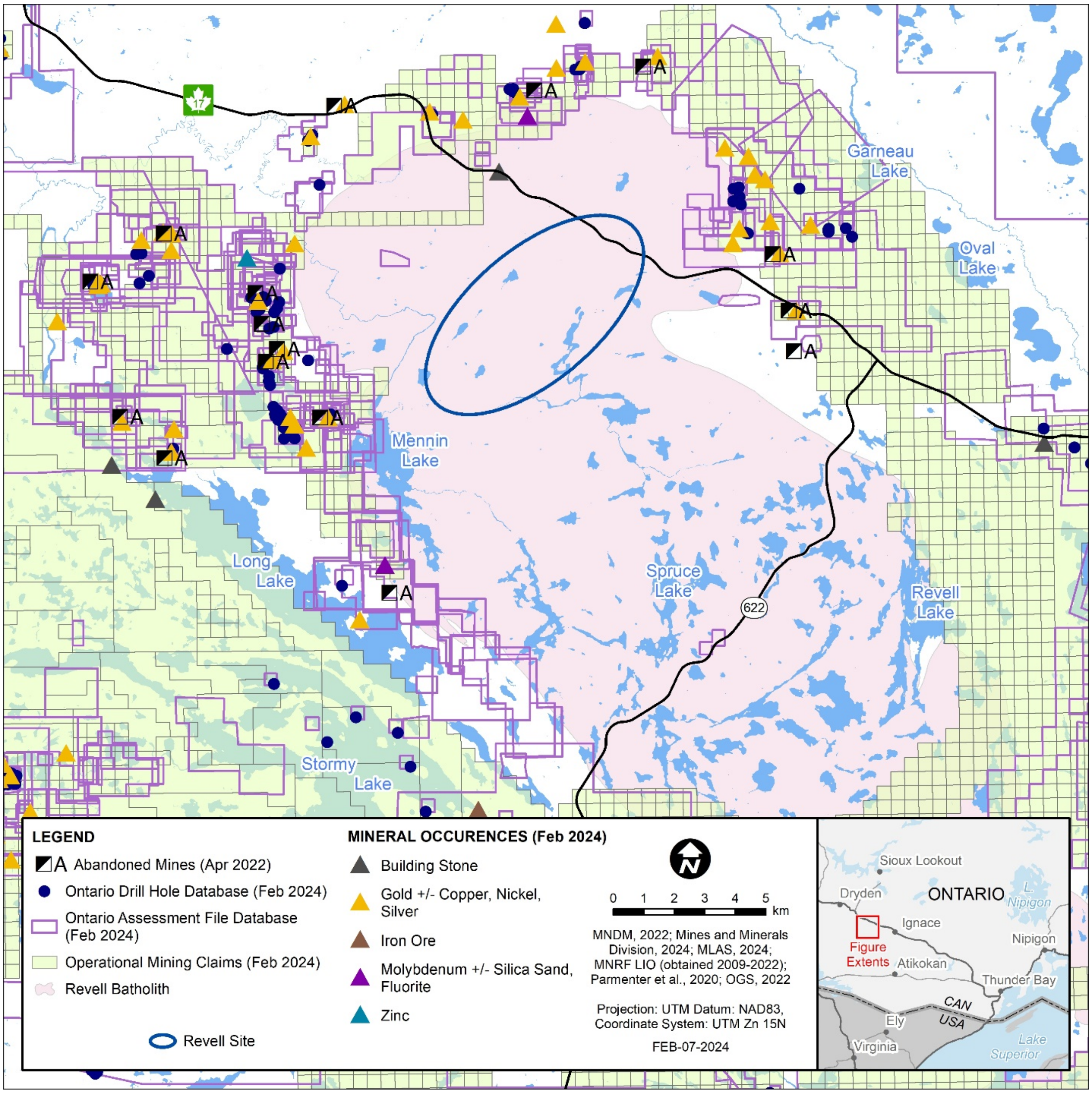

Figure 5.1: Locations of abandoned mines, operational mining claims, mineral occurrences, and exploration work in the vicinity of the Revell Site.

5.2 Groundwater Resources

As described above in Section 3.3, laboratory analysis of groundwater and porewater samples collected during the drilling of the six boreholes indicate that the water at repository depths can be brackish to saline, as is expected in Precambrian crystalline rock (Frape and Fritz 1987). Freshwater conditions begin to transition into a more saline hydrogeochemical environment approximately 300 m below ground surface.

In addition, it is mentioned in Section 3.4, that transmissivity values at the Revell Site generally decrease with depth, consistent with measurements in other crystalline rocks (e.g., Snowdon et al. 2021). At potential repository depths, the site-specific data indicate that the hydrogeochemical conditions, and rock mass hydraulic conductivity values, are not amenable to hosting exploitable groundwater resources, i.e., the water at depth is not fresh and rock at depth cannot supply significant amounts of water even if it was fresh. Furthermore, rock core measurements indicate very low porosity in the intact rock. Transmissivities estimated from packer testing of flowing fracture zones at the Revell Site varies from 10^{-12} m^2/s to 10^{-5} m^2/s.

Of the six boreholes drilled at the site to date, only one flowing fracture zone at depth greater than 400 m was intersected which could potentially have sufficient yield, and water chemistry, for a residential well. However, the observed transmissivity of 10^{-5} m^2/s, and depth of the fracture zone, would make it unlikely to be a resource. A typical water well for domestic water use can produce about 10 litres per minute. There are no domestic drinking water wells in the Revell batholith. Typical bedrock wells in the Ignace area are between 20 and 40 m depth, with a maximum depth of 154 m (Golder 2013).

Based on data collected to date at the Revell Site, the potential for economically exploitable groundwater resources at repository horizon, for drinking, agriculture, or industrial uses, is low.

6. AMENABLE TO GEOLOGICAL SITE CHARACTERIZATION

The Revell Site must be understood sufficiently so that the repository can be appropriately designed to the characteristics of the site, and for there to be sufficient confidence that the site will perform as expected. However, as most of the host rock is not visible, site characterization will only directly measure a small portion of the site.

Therefore, to ensure confidence that the site is sufficiently understood, it is important to demonstrate that the host rock structure and properties are relatively predictable and can be reliably characterized, with uncertainty that is acceptable at this stage of the project.

The Revell Site was identified as potentially suitable in part because the host rock geometry and structure were thought to be sufficiently predictable and amenable to site characterization and data interpretation.

Factors that contributed to this assessment initially were:

- Bedrock exposure is excellent due to minimal overburden, few water bodies, and recent logging activity.
- Batholiths often form as relatively homogeneous volumes of rock. Both the airborne magnetic survey and surface geological mapping results indicated a high degree of lithological homogeneity of the bedrock in the northern portion of the Revell batholith.
- Geological mapping of several long lineaments, interpreted to represent possible fracture zones that extend into the subsurface, are relatively discrete with fairly narrow zones of damage to the bedrock.

Subsequent field testing at the Revell Site has confirmed the relatively predictable nature of the site based on the following:

- Uniformity of the subsurface bedrock, with ~ 95% of the 6 km of recovered core identified as granodiorite-tonalite rock, with relatively consistent mineralogy.
- The orientations of lineaments at the surface on a larger scale are also present in the orientations of fractures in the boreholes at a smaller scale. This understanding provides confidence in the ability to develop meaningful fracture network models on different spatial scales for the site.
- The presence of large fracture zones and subordinate rock types have served to focus deformation, and presumably fluid flow, at various stages during the tectonic evolution of the site. Away from these well understood heterogeneities, the bedrock is characterized as a relatively homogenous and sparsely fractured rock mass.
- Amphibolite sheets, which are a particularly distinct subordinate rock type, are encountered in predictable locations in boreholes, and evident as subhorizontal high-amplitude reflections in seismic data. Overall, they are distributed within north-dipping volumes of bedrock that underly the site.
- The few hydraulically-conductive features encountered in the boreholes are commonly associated with broken (non-cohesive) fractures with gentle dip and subordinate rock types, such as amphibolite. This relationship provides vital information for understanding the current hydrogeological system at the site.

- The consistency between site-specific hydrogeochemical conditions that indicate a near-surface freshwater zone transitioning to saline conditions below 600 m is consistent with an inferred in situ stress model that includes a near-surface stress-relaxed domain down to 300 m and a deep stable stress domain below 600 m.
- Site-specific hydrogeological data can also be explained by the same stress model, and supports the interpretation that a deep stable hydrogeochemical environment is present at the currently proposed repository depth of 750 m.
- Site-specific hydrogeological, hydrogeochemical, and rock mechanics properties are consistent with relevant data from other similar Canadian Shield locations.

These observations provide confidence in the NWMO's ability to characterize and understand the large-scale geometry, structure, and rock properties of the bedrock at the Revell Site.

7. REPOSITORY CONSTRUCTION, OPERATION, AND CLOSURE

The deep geological repository (DGR) can be constructed, operated, and closed safely by:

- incorporating in its design, the best engineering practices and use of known technologies for safe construction, operation, decommissioning, and closure; and
- ensuring the surface and underground characteristics of the site are favourable to the safe construction, operation, decommissioning, and closure and long-term performance of the repository.

For more information on the repository conceptual design including details on the underground and surface facilities, see NWMO's *Deep Geological Repository Conceptual Design Report* (NWMO 2021a).

The following sections elaborate on the development status of the key engineered components and considerations for a deep geological repository at the Revell Site and ongoing work.

7.1 Engineered Barrier System

7.1.1 Used Fuel Container

The used fuel will be placed inside a long-lived used fuel container (UFC). The primary purpose of this container is to contain and isolate the used fuel from the underground environment, preventing water from contacting the used fuel, and so preventing radionuclides in the fuel from escaping into the underground environment.

The reference design concept is a copper-coated steel container with the nominal dimensions described in Table 7.1 and illustrated in Figure 7.1. The steel provides the structural strength to resist the pressure loads that occur underground, and the copper protects the steel from corrosion.

The main reason for the selection of copper is its stability under conditions typically found underground; that is, water-saturated rock and chemically reducing (low oxygen) conditions. There is thermodynamic, experimental, and natural analogue evidence that copper is stable for very long periods under these conditions. A relatively thin layer of copper can last over one million years in the Canadian repository (Hall et al. 2021). (Note that Sweden and Finland use a thick copper shell, where the copper thickness is needed because the copper shell must also be mechanically self-supporting, unlike a copper coating.)

The container is designed to withstand the external pressure loads that would be experienced by the container during its design lifetime in a repository, including the external pressure loads caused by a glacier above the repository up to three-km thick during a future ice age.

The container's design is not finalized and will continue to be optimized post-site selection. The design process considers advances in technology and will be informed by site-specific information and safety assessment evaluations. Changes to the container dimensions, material thickness, etc. are possible.

Table 7.1: Nominal Used Fuel Container Characteristics

Parameter	Value
Length / Diameter	~ 2500 mm / ~ 600 mm
Steel shell	ASME SA-106 Gr.C / SA-516 Gr.70 Pressure Vessel Carbon Steel ~46 mm thick side shell walls; 30 mm thick head walls
Copper coating	3 mm, high purity copper
Number CANDU bundles	48
Mass (loaded)	~2,800 kg
Initial heat load	~165 W
Design basis (glaciation)	3 km thick ice sheet

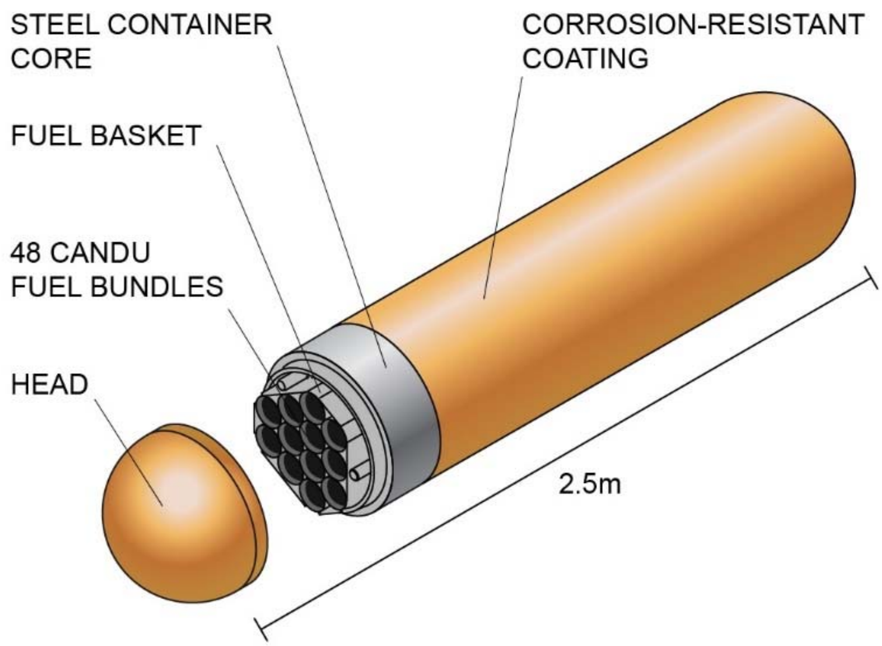

Figure 7.1: Illustration of reference copper coated Used Fuel Container

The reference container is designed for Canada's CANDU fuel bundles and has unique elements to the design, but it shares the key similarities and best practices being investigated and implemented by other leading international waste management organizations. For example, the Swedish (SKB) and Finnish (Posiva) programs have developed a container for light water reactor fuel, with an inner metallic core of cast-iron for structural strength and an outer copper shell for corrosion protection. They are also designing for a future ice age event.

As noted in Section 2, all nuclear generating stations in Canada are CANDU reactors and this fuel type accounts for ~99.9% of all current used fuel. There are plans for new reactors in Canada, which use different technologies and fuel types. In particular, OPG has submitted an application to build a GEH BWRX-300 BWR at its Darlington site. The BWRX-300 fuel is similar to the reactor fuel in other countries, including Finland, Sweden and Switzerland. These countries are all in the process of licensing or building repositories for their used fuel, so their design solutions provide a direction for how the BWRX-300 fuel in Canada could be managed.

As these plans develop, the NWMO will assess the potential of using the current container design for these other fuels. Fuel characteristics, geometry, and other considerations may require alternative or modified container designs to be developed. The NWMO will build on the reference CANDU fuel container, as well as international container designs developed for these fuel types. Any changes to the container design will be co-ordinated with designs for related systems, notably the Used Fuel Packaging Plant and the underground placement operations.

7.1.2 Buffer Materials and Sealing Systems

A swelling clay-based buffer material will surround each container in order to ensure a low-permeability and chemically benign environment around the containers; specifically, the clay buffer greatly slows the flow of water, creates favourable conditions to minimize corrosion, and mechanically holds and protects the container.

The main component of the buffer is bentonite, a naturally occurring clay. These clays are stable, having typically been formed millions to hundreds of millions of years ago. The main mineral in bentonite is montmorillonite. Montmorillonite is responsible for the most distinctive property of bentonite; it can swell to several times its original volume when placed in water. In the confined space of a repository, this swelling causes the clay to seal fractures and gaps, which makes the saturated clay nearly impermeable.

Bentonite clay buffer is a key component of the multiple-barrier system:

- Bentonite's swelling property greatly reduces the ability for water to flow; increasing the time it takes for water to reach or leave the container;
- Bentonite's chemical and swelling properties help supresses microbial activity around the container, preventing or slowing microbial corrosion of the copper; and
- Bentonite slows radionuclide movement in the unlikely event of container failure; reducing the ability for them to reach the surface and biosphere.

The clay can be compressed into a solid block to allow easier handling and improved performance. The used fuel container will be directly surrounded by this highly compacted bentonite. The bentonite is shaped into two halves of a box with a cut-out for the container to be placed inside. The compacted bentonite is strong enough to support the container inside during the transfer and placement activities underground. The upper and lower halves of the bentonite are known as the **buffer box**, as shown in Figure 7.2.

The buffer boxes are placed in the underground placement rooms as shown in Figure 7.3; stacked two containers high. Bentonite clay blocks are placed between buffer boxes for thermal spacing purposes and to fill small voids used for handling and placement. The remaining space between the rock and the buffer box, on the sides and top, is typically less than 30 cm. This space is filled with loose granular bentonite material known as gap fill material.

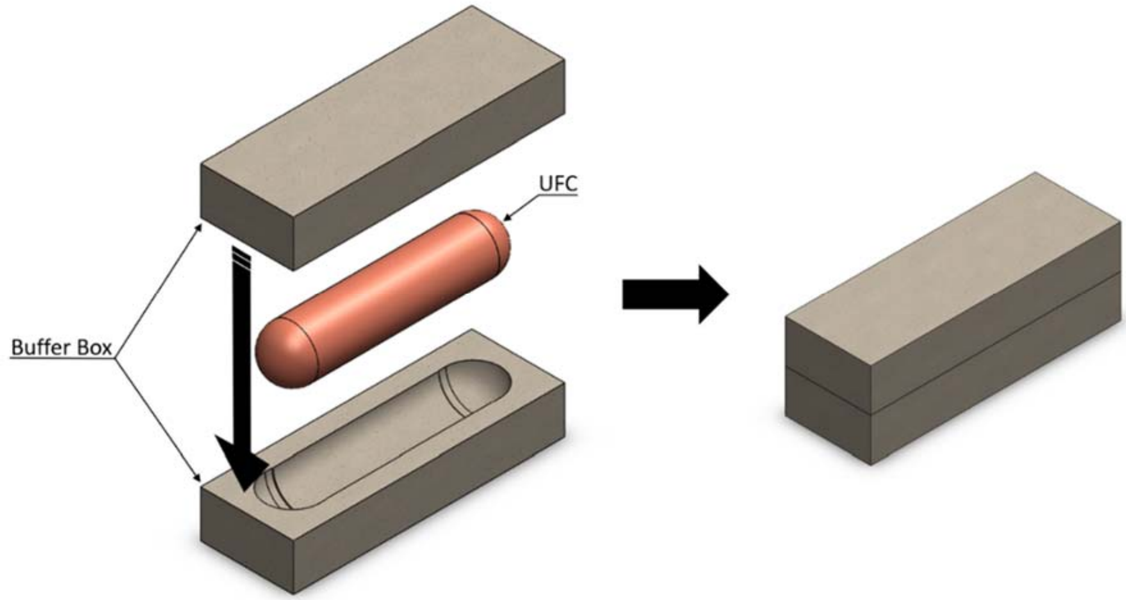

Figure 7.2: Used Fuel Container within a bentonite clay Buffer Box

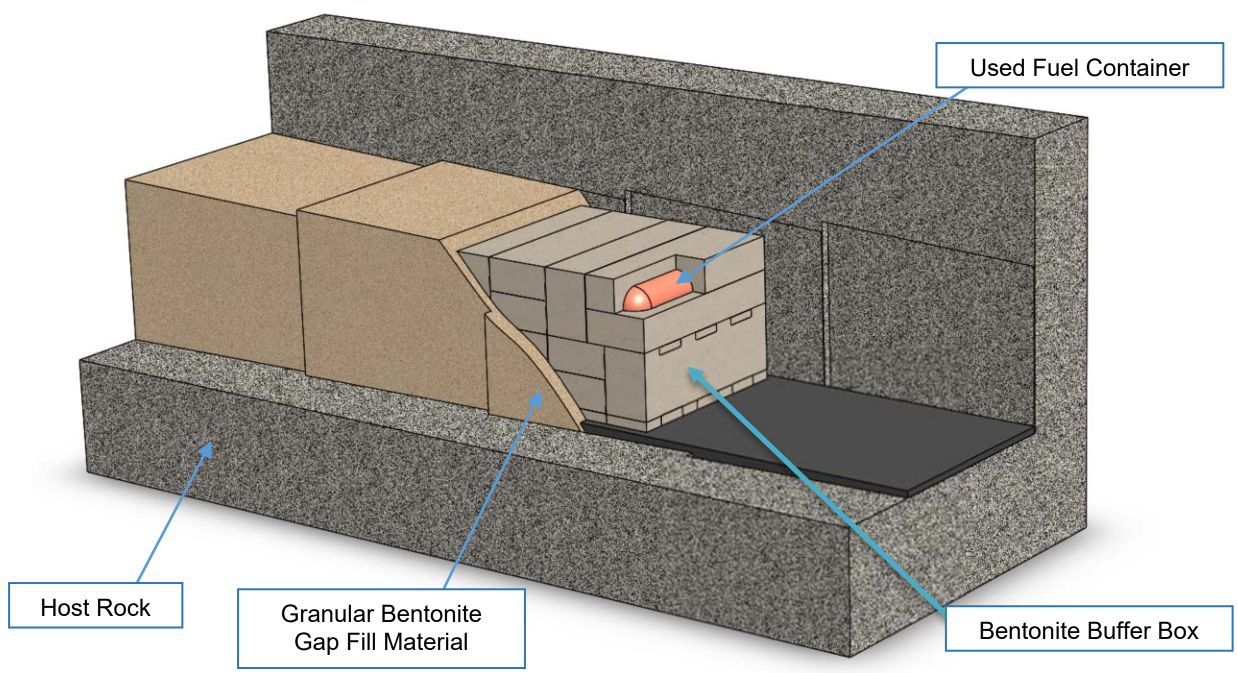

Figure 7.3: Cutaway illustration of placement room concept

The ends of the placement rooms, towards the access tunnels, would be sealed with room end plugs made from bentonite clay and a thick concrete bulkhead. These would isolate the filled rooms from the open access tunnels during the operating and extended monitoring phases, and from the closed and back-filled tunnels in the long-term.

The tunnels and other underground openings would be filled with a mixture of crushed-rock and clay based backfill at repository closure, that provides long-term mechanical support to the surrounding rock and reduces the hydraulic conductivity of these openings. The shafts would be sealed with combination of clays, concrete, rock backfill and possibly asphalt.

It is estimated that about 50 years will be needed to complete the container placement underground for all of Canada’s projected used nuclear fuel (NWMO 2022). This will be followed by an extended monitoring period where tunnels will remain open for access underground. For planning purposes, it is assumed that this period will be 70 years, but it could be longer or shorter. It is important to note that monitoring systems will be designed to ensure no impact to long term safety of the repository. Monitoring is further discussed in Section 12.

After a suitable monitoring period, and in consultation with stakeholders, all tunnels, shafts and surface boreholes would be backfilled and sealed with combinations of rock, clay and concrete. There would be no remaining equipment that needed to be maintained to ensure safety. Post-closure monitoring of the facility would, however, continue for some time in order to confirm the repository was operating as expected.

7.1.3 Engineered Barrier Testing

The proposed container, buffer and seals, and placement concepts build on established elements of a robust repository approach but represents a novel approach to the overall **Engineered Barrier System** (EBS) that has been optimized for CANDU fuel. It leverages proven techniques from nuclear/aerospace coating technologies, robotics and automated handling, and mining industries.

To build on that confidence, a testing program was developed, known as the Proof Test Plan. The Proof Test Plan’s primary objectives were to develop and demonstrate prototype engineered barrier component fabrication and placement. This is described further below.

Materials Testing

In support of the Engineered Barrier program, work has continued to further the understanding of the behavior of the primary materials.

The primary basis for the selection of copper as a corrosion resistant barrier on the containers is the evidence that it is stable on geological timeframes under reducing geochemical conditions. Scientific studies of copper corrosion over the past 40 years by multiple waste management organizations has confirmed the durability of copper for use in geological disposal. NWMO studies in this area are summarized, for example, in Keech et al. (2020) or the NWMO Annual Technical Reports (e.g., Briggs 2023).

Small scale copper samples have been subjected to a variety of tests, such as corrosion, mechanical strength, and coating adhesion. For example, copper-coated specimens for materials testing have been placed deep underground in Switzerland as part of international joint projects, and have been placed one km deep in the Pacific Ocean for pressure and saline water corrosion tests. In 2021, copper coated test samples were placed 0.3 km underground in a borehole at the Revell Site in order to experience the specific chemistry of the rock at that location. Also, copper coating test samples are being exposed to high levels of radiation under long-term exposure tests at Chalk River National Laboratories.

These tests have provided support for the development of a detailed understanding of copper corrosion under conditions relevant to geological disposal and supported the prediction of its long-term durability as a corrosion barrier.

<u>Container Fabrication and Testing</u>

Under the Proof Test Program, 12 full scale containers (10 copper coated and 2 steel-only vessels) were fabricated (and several partial containers). The prototyping process has resulted in improved fabrication methods, full-scale demonstration of inspection methods, and allowed various structural tests to be performed.

As the program advanced, larger scale samples and testing were conducted. For example, Figure 7.4 shows a full-scale cross-section of a container being subjected to a beyond design basis loading scenario known as a crush test. The load far exceeds what is expected for the container in the repository, even beyond the bounding loads caused by the next ice age. The testing demonstrated the ability of the steel and weld zone to deform without breaking, and the copper coating remained well bonded under these extreme conditions.

Another key test was the external pressure testing of full-scale prototype containers. Four external pressure tests have been conducted to date. Figure 7.5 shows the external pressure test of a copper coated container at the Applied Research Lab at Penn State University in 2016. In this test, a container was placed into a test chamber where it was subjected to a hydrostatic pressure equivalent to being under almost six kilometres of ice. This pressure exceeds the maximum total pressure expected in the repository (including 3-km-thick glacier in future ice ages).

Figure 7.6, Figure 7.7 and Figure 7.8 present the latest external pressure test of a steel UFC prototype at C-FER Technologies in Edmonton in 2022. In this test, the prototype container survived 10 cycles of the bounding design pressure (i.e., including the load from 3 km of ice above the site during future glaciations) without any visible change of shape and dimensions, as shown in Figure 7.7. The container was then loaded to 1.4 times the bounding design pressure in order to force it to buckle and collapse, as shown in Figure 7.8. Helium leak test after the collapse showed that the container was still leak tight.

The external pressure tests along with other tests have demonstrated that the UFC design is structurally sound to withstand the significant hydrostatic pressure load that may occur in the repository, including the bounding design pressure during future glaciation cycles. The tests also demonstrated that even if the UFC loses its structural stability (i.e., buckles and collapses), the UFC materials are sufficiently ductile to maintain the containment boundary (i.e., remain leak tight). In addition, the pressure test also provided validations for the design analysis techniques and computer simulation models, which enhances confidence in future design outcomes generated by these techniques and models.

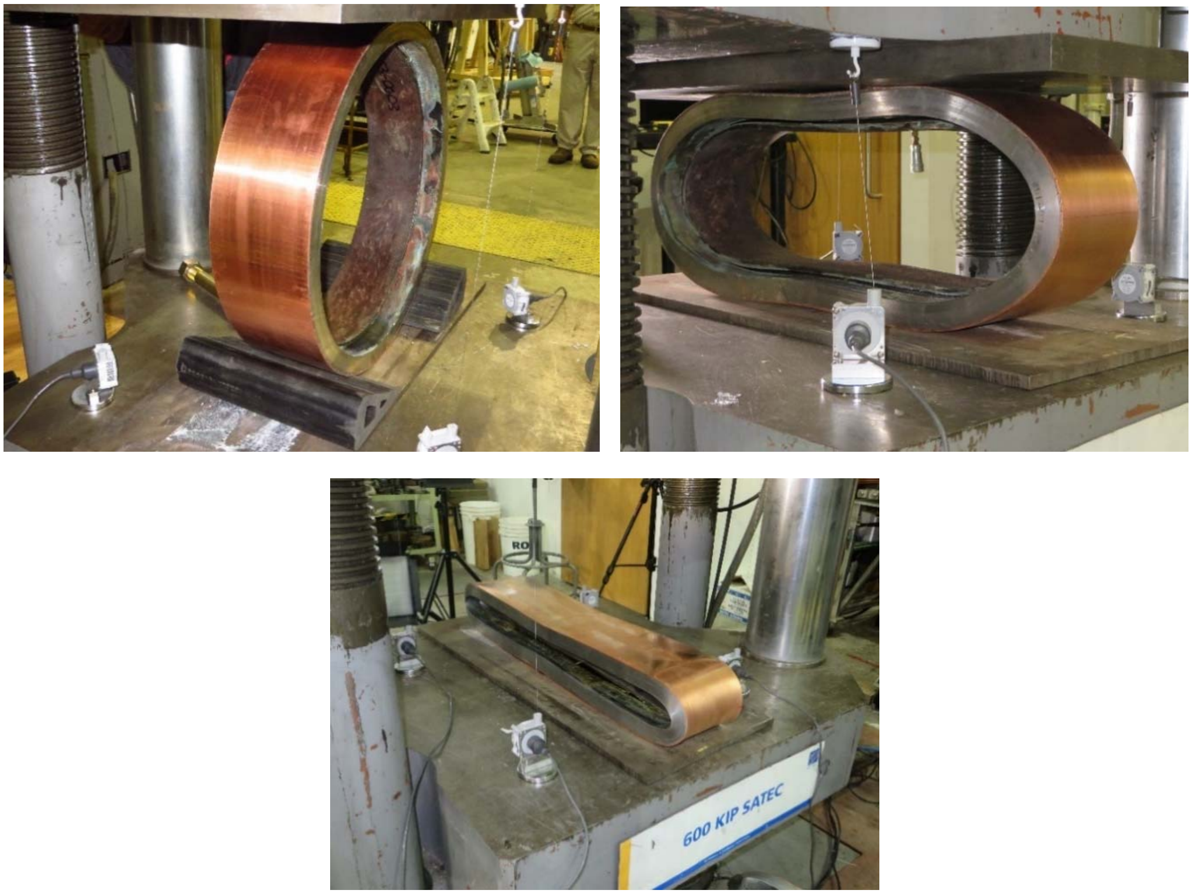

Figure 7.4: Used Fuel Container cross-section undergoing a beyond-design-basis crush test. Copper coating remained bonded to steel.

Figure 7.5: Copper coated prototype Used Fuel Container external pressure test at Penn State University in 2016. (Left) Test chamber lid being lowered into place; (Right) Container removed after experience more than 1.2 times the bounding design pressure; no significant change of configuration.

Figure 7.6: Steel prototype Used Fuel Container external pressure test at C-FER Technologies in 2022. The container is being inserted into dual-walled test chamber.

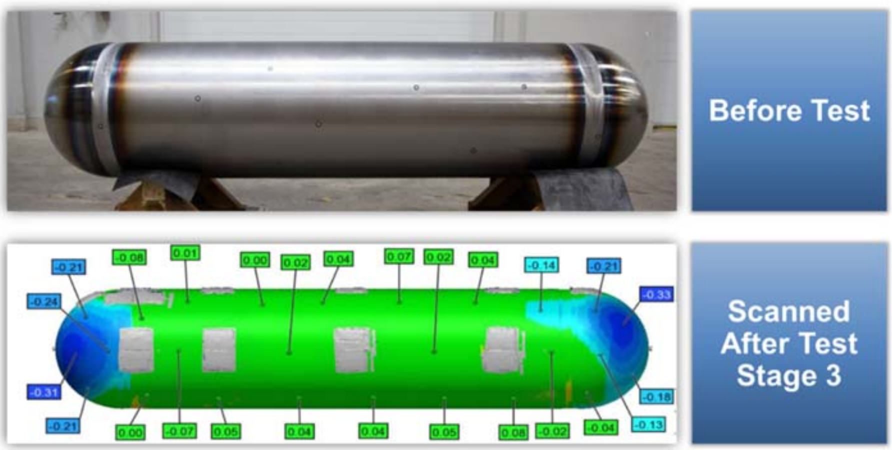

Figure 7.7: Steel prototype Used Fuel Container external pressure test. Photo shows container before and after 10 cycles of bounding design pressure including glacial load.

Figure 7.8: Steel prototype Used Fuel Container external pressure test. (Left) container buckled and collapsed under pressure 1.4 times the bounding design pressure; (Right) helium leak test to verify that the container is still leak tight after collapse.

Buffer Fabrication and Tests

As of mid-2023, fabrication of more than 10 buffer boxes have been completed, as shown in Figure 7.9, and various improvements to the design and fabrication methods have been achieved.

For example, initially these buffer boxes were constructed out of smaller bricks that were assembled into a larger box that required a steel frame. Further design work led to the development of a half-buffer box as a single unit that can fully hold the container. This innovation allows for easier handling and assembly of the completed buffer box and eliminates the need for a frame. Testing of different ways to handle the buffer boxes using both a combination of vacuum lift and forklift style technology are shown in Figure 7.10.

Figure 7.9: Prototype Buffer Box and Used Fuel Container

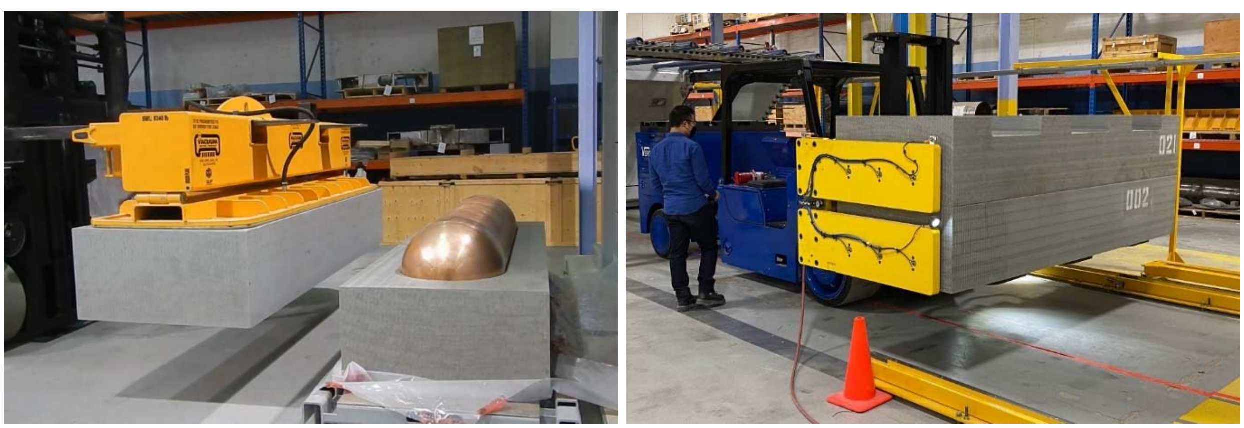

Figure 7.10: Bentonite handling: (Left) Using vacuum lift technology; (Right) Robotic forklift handling of buffer box.

Placement Test

The full-scale placement trial was conducted at the NWMO's Discovery and Demonstration Center over the course of a week in 2022 (Figure 7.11). This trial was the culmination of several years of engineering development of the Engineered Barrier System. Its main purpose was to demonstrate the effectiveness of the NWMO's engineered barrier system by testing, assembling, and placing full-scale prototype system components in a simulated placement room. This allowed the NWMO to perform an operational demonstration of the reference concept, a verification of equipment performance and an assessment of the feasibility of the reference concept in achieving placement of the Used Fuel Containers (UFCs), the bentonite buffer and backfill. The placement trial was successful and met its objectives.

Figure 7.11: Mock Placement Room and Testing at the NWMO's Discovery and Demonstration Center

During the test, buffer boxes were picked up with the delivery equipment (Figure 7.12), trammed down the length of the room and placed. Each buffer box was positioned precisely, and a post-placement inspection was performed to document the position and condition of each buffer box assembly. The buffer box delivery equipment performed as expected and demonstrated that placement of buffer boxes is feasible (Figure 7.13).

Figure 7.12: Buffer Box Delivery Equipment

Figure 7.13: Buffer Boxes in Placement Room

As with the buffer box delivery equipment, the gap fill delivery equipment (Figure 7.14) also performed as expected (Figure 7.15). Various measurements and inspections were performed throughout the trial confirming that the results met requirements for positioning and density of the buffer material, successfully demonstrating the NWMO placement concept.

Figure 7.14: Gap Fill Material Delivery Equipment

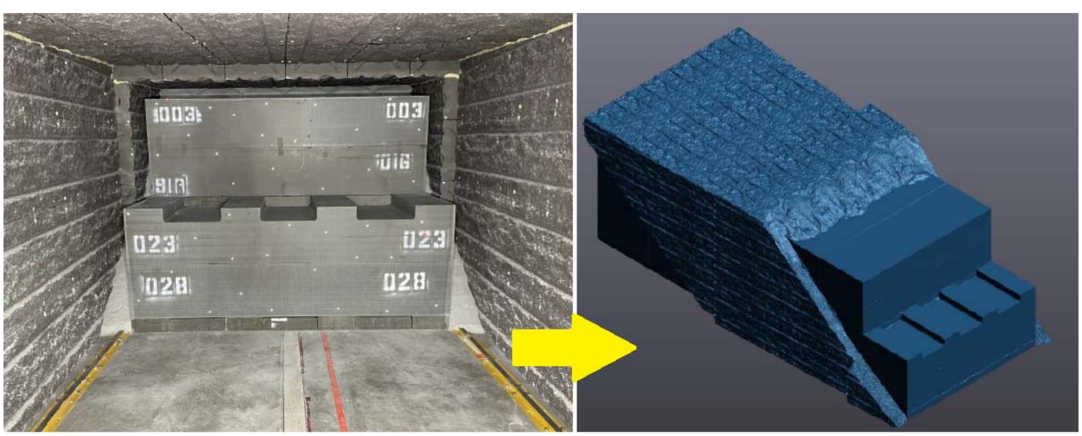

Figure 7.15: Gap Fill Material Placed around Buffer Boxes and 3D Scan

7.2 Underground Facilities

Based on the site-specific information, the NWMO is considering placing the repository within a depth range of 650 to 800 m, in the current design study around 750 m, in order to place it within the deep stable geosphere at this site. The actual depth will be finalized based on more detailed information on the geology of the site.

The underground repository is largely a network of access tunnels and placement rooms that will contain the used fuel within the engineered barriers. Placement rooms make up the largest volume of the underground area; however, there are several supporting facilities located within a centralized services area.

7.2.1 Shafts

Access to the underground would be by vertical shafts. Other repositories planned around the world use shafts, ramps or a combination, based on repository depth, local geology and other factors. A discussion of these factors is provided in Lee and Heystee (2014).

For the proposed repository depth and the nature of the Revell site, and consistent with Canadian mining experience, access to the repository would be through three shafts. These shafts are:

- Main Shaft Complex: for transfer of the used fuel container in buffer boxes;
- Service Shaft Complex: for movement of personnel, mining materials, and excavated rock, as well as main air intake; and
- Ventilation Shaft Complex: for repository exhaust air; it also provides secondary means of egress for personnel during an underground emergency event.

The NWMO's reference plan is that the three shafts will be developed using conventional controlled drill and blast. As the shafts are excavated, the walls will be lined with concrete (a hydrostatic liner). The design of the shaft liner will be completed after the location of the shaft (and site) is established. The shaft liner will serve two purposes; first it provides ground support, preventing minor ground shifts or loose rock from falling into the shaft, and second it will minimize seepage of water into the shaft.

As part of the repository closure activities, the shaft liner would be removed where needed, and the entire shaft backfilled with sealing materials to provide a durable long-term barrier. The sealing materials and placement will be optimized based on the geology, and would likely consist of regions with concrete and regions with bentonite-clay based seals. Asphalt may also be used as third independent sealing material.

7.2.2 Central services area

Underground, the services area acts a central base of underground operations and has the following facilities:

- Main, Service, and Ventilation shaft access;
- Underground Demonstration Facility;
- Refuge stations, offices, lunch area, washrooms;
- Maintenance shop and warehouse;
- Battery charging station;
- Equipment / material storage areas;
- Explosives and detonators magazines;
- Main electrical substation; and
- Truck dump equipped with grizzly and rockbreaker.

7.2.3 Underground placement rooms and access tunnels

From the services area, twin access tunnels branch out forming various “arms” that lead into placement panels. The NWMO has selected this adaptive layout design primarily to accommodate the geology, and to provide flexibility during construction and operation.

As with most crystalline rock, the Revell site rock has natural fractures that range in size from microfractures to large lineaments visible at surface. Some fractures are naturally sealed by age or by underground pressure. However the underground layout would be designed to avoid or maintain a distance to major fractures. This is illustrated in Figure 7.16 for a generic crystalline site. These fractures are determined before construction using boreholes and seismic studies, and during construction they are confirmed through drilling long pilot holes and through tunnel excavation. Placement rooms would also be designed to maintain a distance to any site characterization boreholes, again as illustrated in Figure 7.16, even though these will be sealed on closure.

Based on current information, Figure 7.17 shows where underground placement rooms and service area could be located at the Revell site. The site-specific underground layout would be developed in future incorporating further field investigations on fracture locations and on the in situ stress direction. However, layout development has confirmed that the Revell has sufficient area available for the current used fuel projections (NWMO 2022) and for expansion should that be agreed.

The placement rooms would be about 300 m long and about 25 m apart, based on structural and thermal considerations; in particular, to ensure that the temperature at the container surface is limited to 100°C (Leupin et al. 2015). Containers will be placed in these rooms and surrounded by a clay-based buffer material to ensure low-permeability and chemically favorable conditions. The room ends would be sealed with bentonite clay and a concrete bulkhead plug.

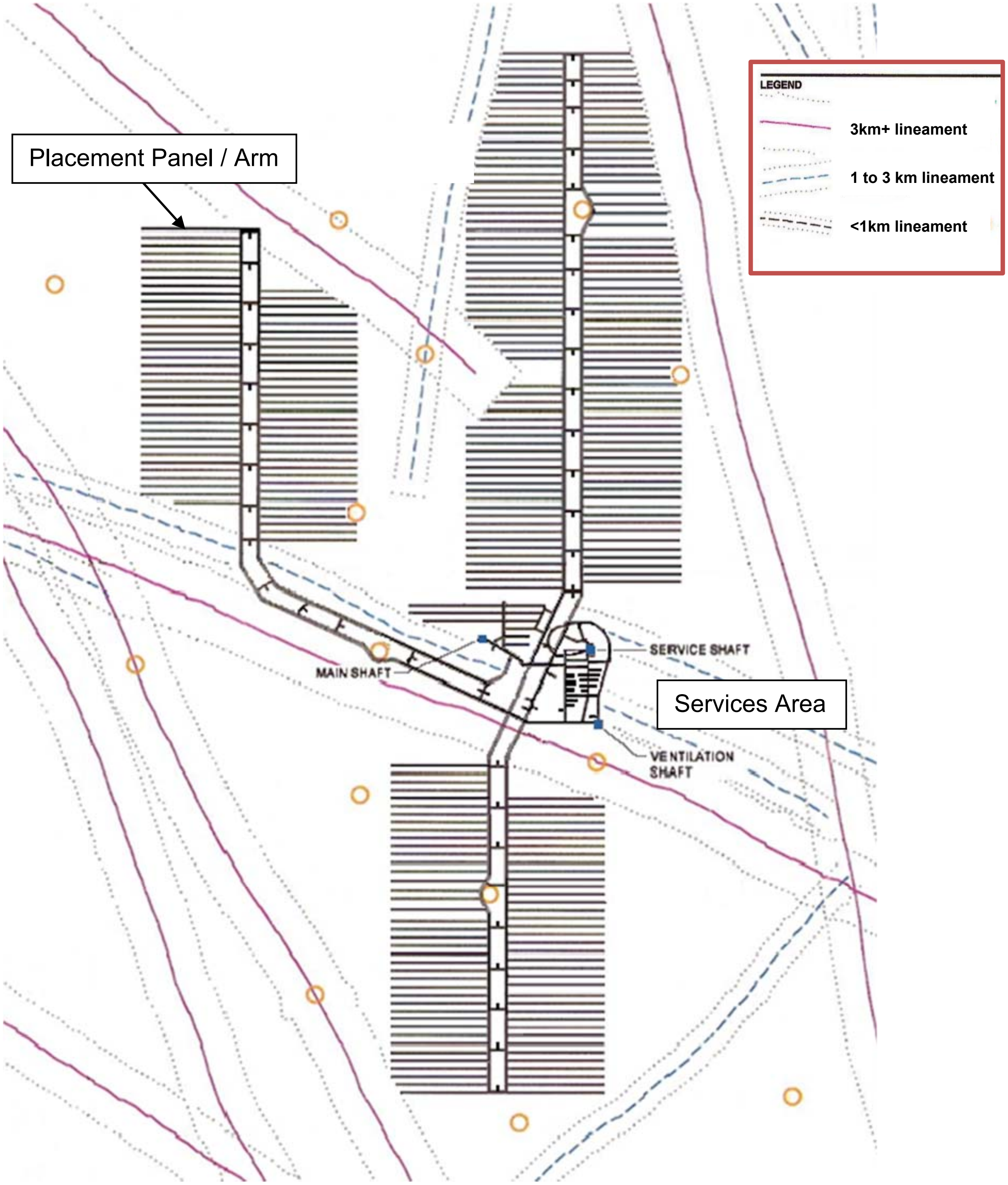

Figure 7.16: Conceptual underground layout for a hypothetical crystalline rock site, showing positioning of placement panels to fit within the geological lineaments. Open circles represent example borehole locations. Lineaments and layout are for illustration purposes and are not Revell site specific.

Figure 7.17: Potential underground area at Revell Site that could be used for placement rooms and central service area, based on space between major lineaments. Figure shows the area needed for base case inventory (blue) and potential areas that could be used for expansion (yellow).

For the crystalline rock at the Revell Site, excavation of the underground openings at the repository depth does not represent a technical problem. This rock is mechanically strong. There is much experience in this type of engineering in mines in Canada. There will likely be concrete floors, concrete bulkheads and local roof support, for example, rock bolts, grout, and/or shotcrete in the services area and access tunnels. Excavation techniques will be adopted that minimize the extent of the rock excavation damaged zone that typically forms around mined excavations.

During operations, individual placement rooms will be filled and sealed, including installation of concrete plugs at their connection to the access tunnels. However, the access tunnels will remain open during operations and through the extended monitoring period, such that access to the placement rooms is maintained. When the repository is closed, the tunnels will be backfilled.

7.2.4 Underground Ventilation

The underground equipment is expected to be primarily electrical; this will reduce ventilation requirements compared with use of diesel equipment. The used fuel containers are sealed closed, so would not be a source of release of radioactivity underground.

The underground ventilation system uses a series of surface fans, underground booster fans, ventilation doors and regulators to control airflow distribution, and to ensure a ‘one-pass’ ventilation loop into and out of the repository. Most of the exhaust air will be directed out the ventilation shaft with a small amount out through the main shaft. Inflow air will be directed through the service shaft. The exhaust ventilation stack and the main shaft vent stack will be equipped with High-Efficiency Particulate Air (HEPA) filtration systems. During excavation and normal operations, this system would be bypassed as the exhaust air does not need filtration. These systems will be activated in an emergency, notably if radioactivity is detected in the underground air at above-background concentration levels.

In case of emergency, staff will be evacuated to surface or shelter in place following established procedures. Two of the three shafts are equipped to move personnel to/from the surface. The service shaft and the ventilation shaft acting as secondary egress. If evacuation is not immediately possible, a permanent refuge station is included in services area. It will have concrete walls and steel door for fire protection. The refuge station will be equipped with safety and rescue equipment such as a fire extinguisher, eyewash station, first aid kit, emergency food and drink rations. The station can be fully sealed with fresh air supplied via the compressed air system with appropriate backup. Additionally, portable refuge stations will be placed underground in strategic locations in the access tunnels where excavation and placement activities are occurring. They can be fully sealed and will use compressed air bottles for emergency breathing air. They will be stocked with similar safety equipment and rations as the permanent refuge station.

7.3 Surface Facilities

A description of all surface facilities is provided in the 2021 DGR conceptual design report (NWMO 2021a). A conceptual layout for the surface facilities is shown in Figure 7.18.

The surface facilities will be divided into two types of areas: the Protected Area and the Balance of Site. The Protected Area includes surface facilities that require restricted access, including the Used Fuel Packaging Plant and all shaft complexes providing access to the underground. Security check points and double perimeter fencing will prevent unauthorized access into the Protected Area. Surface facilities located outside the Protected Area, but inside the outer perimeter fence, are considered the Balance of Site. Key facilities in the Balance of Site area will include the Administration Building, Sealing Material Compaction Plant and a Concrete Batch plant. An Excavated Rock Management Area (ERMA) will be established outside of the repository perimeter fence to manage the waste rock from underground operations.

The following sections discuss some of the key facilities at surface.

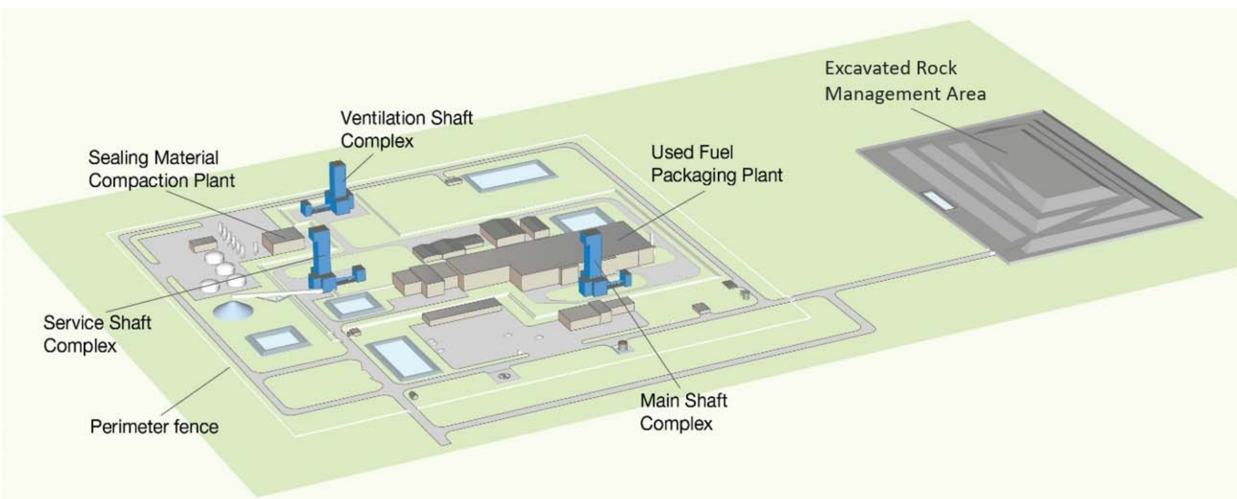

Figure 7.18: Illustration showing conceptual DGR surface facility layout

7.3.1 <u>Site Security</u>

The Protected Area boundaries will consist of a physical protection system, with controlled personnel and vehicle access points consistent with current Nuclear Security Regulations (SOR/2000-209). Additionally, the entire surface facility will be surrounded by a fence in order to provide controlled access to vehicles and persons and to prevent intrusion of wildlife.

The Protected Areas physical protection systems will incorporate a perimeter barrier with unobstructed land of minimum 5 m clear distance on both sides of the barrier. In addition, a system of protective elements will be in place to provide multiple layers of delay, detection and assessment that are controlled through a central command post or security monitoring room. The assessment component will enable security personnel to evaluate detected threats and provide the appropriate response. All these component layers will further be connected to a back-up uninterrupted power supply, located within the Protected Area.

Nuclear Security Regulation (SOR/2000-209) stipulates that the detection and assessment components must each feature two independent systems. The delay component must have additional capabilities to deny intruders using large vehicles from forcing entry. Consistent with these requirements, the systems established to secure the Protected Areas will include:

- A physical barrier to delay intruders for a sufficient period of time to enable effective interception by response personnel and provide sufficient time delay at all points around the perimeter of the facility. The reference design includes two fences approximately 3 m high and 3 m apart with lighting.
- A detection system to identify intruders immediately and alert security and response personnel. The reference design includes various remote sensors outside and attached to the security fences to alert security of access attempts.
- An assessment system, with a dedicated lighting network, to allow security personnel to clearly identify and quantify any possible intrusion. The reference design includes a network of CCTV cameras throughout the Protected Area including the security fence.

7.3.2 Used Fuel Packaging Plant

The Used Fuel Packaging Plant (UFPP) facility receives and opens the used fuel transportation package, removes and inspects the used fuel, and transfers the fuel into a used fuel container. There is no reprocessing of the fuel. The container is sealed, inspected, and placed inside a buffer box. Figure 7.19 illustrates the main steps.

All handling operations that involve used fuel will be completed within heavily shielded enclosures (i.e., hot cells). Fuel handling will use remote tooling and shielded transfer packages. All shielded cells will be environmentally controlled by a filtered ventilation system to prevent the spread of airborne radioactivity.

Specifically, all areas of the UFPP will be zoned and controlled according to external dose rates and the potential for radioactive contamination. Ventilation systems will be designed such that each zone will be under a negative pressure, with the highest potential contamination areas kept at the lowest pressure. This controls the air flow, causing it to move from zones of lower potential contamination to the zone of highest potential contamination. The negative pressures are maintained with an exhaust system that filters and monitors the air through High-efficiency Particulate Air (HEPA) filters before releasing it the environment. Radiation monitoring and redundancies would be in place to ensure releases are safe and meet all applicable regulations and standards.

The UFPP will also include the required auxiliary systems, like electrical power systems (regular, emergency and back-up), a central control room, waste management facility, and facilities for personnel. Maintenance on used fuel handling equipment will be performed within the UFPP.

The UFPP will be designed considering upset events, such as earthquakes or fire. The facility will be designed to safely shut down. Emergency power, provided by onsite generators, and additional battery back-up power, ensure critical safety systems are able to keep functioning in the event of an emergency. Fire protection and suppression systems will follow industry best practices including national standards for facilities that handle nuclear materials.

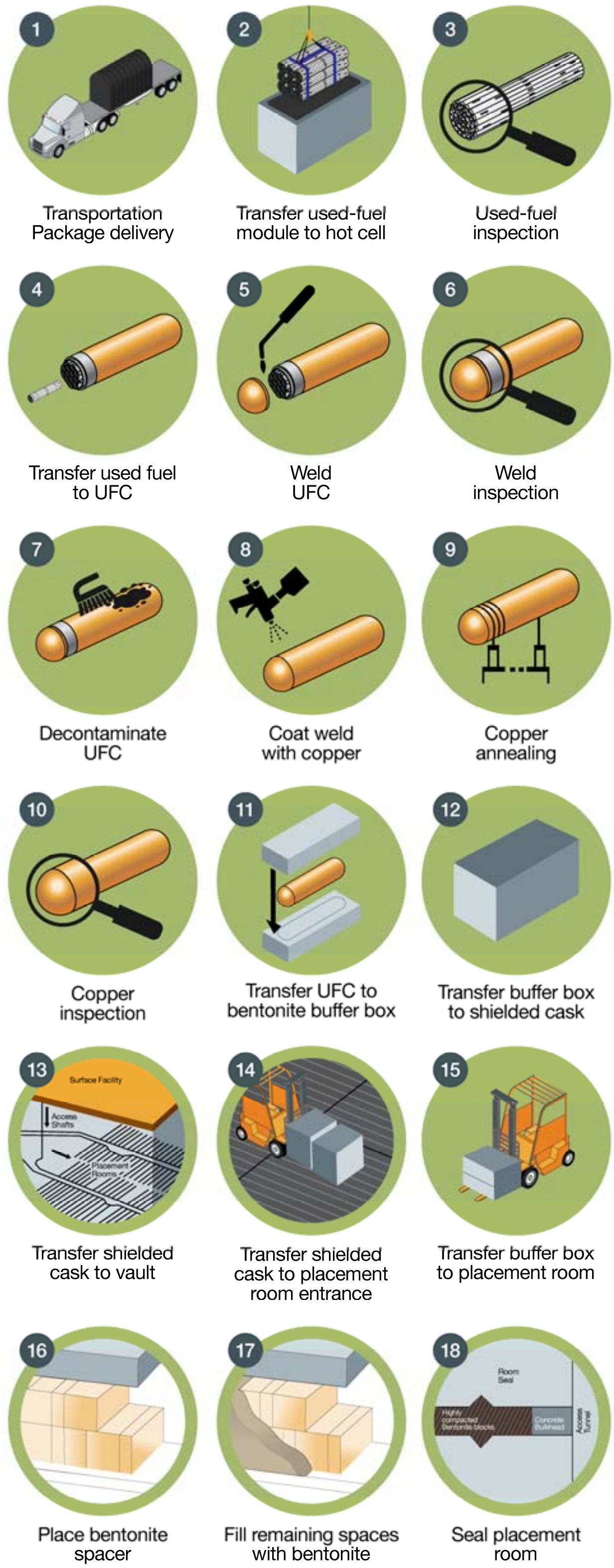

Figure 7.19: Illustration of the main steps with handling and emplacing the used fuel at the repository site.

7.4 Emissions and Waste Management

7.4.1 Water Management Systems

The repository surface and underground facilities need water to facilitate construction and operations. The NWMO's facilities will meet all applicable regulations and requirements for water taking, treatment, monitoring and discharge back to the environment.

At the Revell Site, it is anticipated that water for the surface facilities will be sourced from a nearby surface water body (i.e., lake) or well. Potable water will be produced on site at a water treatment plant.

Sewage collected from all serviced buildings will be piped to an on-site sewage treatment plant for treatment to all applicable regulations prior to recycling or discharge to a local water body. Collected sludge will be disposed off-site following all applicable regulations.

Site stormwater run-off will be collected and diverted to several stormwater managements ponds. All the ponds will be lined, as required, over their base and embankments for protection and to prevent water infiltration back into the ground. Collected water will be monitored and treated, as required, prior to discharge in accordance with all applicable regulatory limits.

As with any underground excavation (e.g., mine), water can accumulate underground from several sources, including water used for the drilling. At the repository, this water is collected in underground sumps and treated underground in order to recycle water where possible. Any remaining water will be piped to a dewatering settling pond. This water in the settling pond may contain sediment (rock dust), nitrogen compounds (arising from the explosives used to excavate rock), salt (due to saline ground water inflow into underground repository), particular elements released from the rock (notably uranium), and hydrocarbons (oils from equipment). If the concentration of these potential chemical contaminants are above acceptable levels, then the water will be treated before being reused as service water or discharged into a receiving water body following all applicable regulatory limits. The design is considering best practices to ensure reuse of the water for the underground operations (e.g., as service water) where possible.

The design of all stormwater and settling ponds will be in accordance with the Ontario Ministry of the Environment Conservation and Parks design manual (MOE 2003).

7.4.2 Excavated Rock Management Area

An Excavated Rock Management Area (ERMA) is a separate facility that will receive the excavated rock from underground construction over the life cycle of the facility. The ERMA location will be within a 5 km distance of the repository shafts, and will be selected to minimize impact on streams and wetlands. For a repository with a capacity of about 5.5 million CANDU fuel bundles (NWMO 2022), the rock pile with stormwater ditches would occupy an area of approximately 700 m x 700 m with a rock pile height of 15 m. This is larger than previously estimated because it is based on a more accurate assessment of excavated rock, it includes the stormwater ditches around the rock pile, and it partially considers the land topography. The final design dimensions will be determined after the ERMA site has been identified.

A key component of the ERMA is water management. This includes storm water management to collect run-off flows via perimeter ditching, consolidation of run-off into a settling pond, and monitoring water quality (e.g., suspended solids, chemical contaminants, etc.) to ensure compliance prior to discharge. If required, the storm water would be treated according to all applicable regulations prior to discharge to the environment.

A key design consideration for a mining rock pile is whether the rainwater that falls on and percolates through the rock pile becomes acidic or has a high concentration of metals or salt. This is determined in advance through standard laboratory leachate tests. For example, these types of tests can determine if the excavated rock is potentially acid generating (PAG).

Preliminary testing of rock core from the Revell Site determined that the rock at repository horizon is non-PAG; however, a comprehensive testing program to confirm this will be conducted during the detailed site characterization.

If the rock is found to be acid-generating or have other concentrations of concern, then the ERMA will be designed to limit the amount of leachate that could seep into underlying soil and rock. This is achieved by segregating formations that may need additional treatment within the ERMA and with a liner system including the main rock pile area, the perimeter ditches, and the stormwater management pond. The storm water would then be treated according to all applicable regulations prior to discharge to the environment.

The rock pile will be rehabilitated after excavated rock placement has ended. The pile can be shaped and restored by vegetating the surface with native plant species and in manner capable of supporting a self-sustaining ecosystem.

The ERMA has been conservatively sized for all excavated rock and assumes no use of the rock for other purposes (e.g., granular grade for road base, etc.). This will be investigated as part of detailed site characterization.

7.4.3 Atmospheric Emissions

The main air emissions from the facility are expected to be:

- Dust as a result of site construction and underground excavation;
- Combustion products from use of diesel equipment;
- Combustion products from use of gas or oil heating and power supply equipment; and
- Low levels of radioactivity from the packaging plant as a result of fuel handling, and from the underground ventilation and the waste rock area as a result of natural radon in the rock.

The primary locations of the air emissions would be the waste rock management area, the underground exhaust shafts and the used fuel packaging plant. Other sources would be smaller and distributed, for example, vehicles.

Dust would be mitigated through good management practices, such as water spraying of surfaces.

Combustion product emissions would be minimized through use of mostly battery electric equipment underground. Any diesel equipment and vehicles would be procured to meet the relevant emissions standards.

Radiological emissions from the facility operations would be primarily from the used fuel packaging plant, where the used fuel bundles are transferred from the transport packages and sealed into their final containers. This handling may generate small amounts of gaseous or particulates within this facility, and any air emissions would then be controlled through the filtered ventilation system. Natural radon would also be released from the rocks underground or from the excavated rock management area. The crystalline rocks within the Revell site do not contain significant amounts of uranium. Therefore, radon would be present, but it is not expected to be a significant emission (Liberda 2020). Radiological emissions would be monitored to ensure they are within the site licence limits, and well below the regulatory limit.

Noise levels would be monitored and managed, and meet regulatory limits and guidelines, including municipal bylaws. The facility would generate noise and ground vibration during site preparation, construction and operation. The noise would be from the equipment, and from blasting during the initial stage of the shaft construction. As there would be continued excavation of underground placement rooms throughout the operations period, there would be continued noise at surface due to the movement of the waste rock to the excavated rock management area. The ground vibration would occur during initial construction due to near-surface blasting for the shafts. Once underground, excavation at the repository horizon would not create noticeable ground vibration at surface.

The transport vehicle fleet would meet current vehicle emission standards and would be maintained, which would minimize emissions and noise. The transport of used fuel and materials to the site would generate air emissions and noise from the vehicles over the travel routes. Assuming road transport, it is estimated that there would be about two shipments per day of used fuel to the site on average, so this would be an intermittent source along the route.

An Environmental Compliance Approval would be required from the province for non-radiological emissions, and radiological emissions would be monitored and controlled within the site licence limits set by the CNSC. An environmental management program would be in place to minimize environmental impacts.

7.4.4 Active Solid and Liquid Wastes

Small volumes of low- and intermediate-level radioactive wastes would be generated, mostly in the used fuel packaging plant.

The modules and baskets from the incoming used fuel transport packages would be the most significant source of active solid waste. After a module or basket has been emptied of used-fuel bundles, they would likely undergo volume minimization prior to disposal. NWMO is investigating potential for reuse and/or decontamination. Active solid waste would include HEPA filters used in ventilation exhaust air, as well as spent filters from the treatment of active liquid wastes. Solid low-level wastes would include those from container fabrication machining, general decontamination and cleaning activities, and used personal protective equipment. Fuel handling equipment and hot cell materials during decommissioning would also be a source.

Underground waters may contain low levels of natural radioactivity (from uranium in the rock) or from maintenance activities at surface. Active liquid waste from the used fuel packaging plant would originate from the decontamination of used-fuel modules and used fuel transportation packages, and from packaging cell cleaning. However, the general design basis avoids use of water especially in contact with the used fuel. For example, fuel would arrive dry and would be stored, handled and packaged dry. Also, the final container copper coating process is cold spray, which avoids water. These will minimize the amount of active liquid wastes.

These active wastes would be handled according to the specific waste stream. For example, active liquid wastes would be filtered to remove most radioactivity. Some of the solid active wastes may be placed in a dedicated underground placement area within the DGR. Others may be sent to licensed external waste management facilities.

7.4.5 Industrial Waste

There would be conventional (non-radiological) waste streams generated at the DGR. Nonhazardous wastes include domestic waste, industrial/process waste, recyclable waste, excess soil and treatment solids, stabilized sewage sludge, reusable/repairable equipment and materials, and compostable waste. Hazardous wastes would include waste oil and grease, batteries, solvents and cleaning agents, and paints, aerosol cans and bonding agents. All conventional waste materials would be sent to a disposal facility that is licensed to accept these types of waste materials. The routine industrial wastes would be sent to a commercial landfill site or to a licensed landfill site that may be created within the repository area.

7.5 Site-Specific Characteristics for Construction, Operations, and Closure

Site-specific factors important to the safe construction, operation, and closure include:

- The surface area should be sufficient to accommodate surface facilities and associated infrastructure;
- The surface facilities can be placed to minimize risk from natural events;
- The soil depth over the host rock should not adversely impact repository construction; and
- The strength of the host rock and bedrock stress at repository depth should allow the repository to be safely excavated, operated and closed.

7.5.1 Surface Area and Infrastructure

A key evaluation factor for site selection confidence is that the surface area is sufficient to accommodate surface facilities and associated infrastructure.

The area around the Revell Site is boreal forest with lakes, wetland and areas of exposed bedrock as shown in Figure 1.1. Portions have been harvested for trees within the past 50 years, so there are already logging roads through the area. The area has moderately undulating topography.

Figure 7.20 below shows the current conceptual surface facility locations within the Revell Site. The site has suitable and ample surface area for the construction and operation of DGR surface facilities, excavated rock management area, and construction camp. The layout shown will change in detail as the NWMO advances the design and continues to incorporate site-specific data.

In terms of existing infrastructure, the Revell Site is within 10 km of Trans-Canada Highway 17, the Canadian Pacific rail line, electrical transmission towers, and the TransCanada Canadian Mainline natural gas pipeline as shown in Figure 7.20.

Based on information to date, the NWMO is confident that there is sufficient surface area for the surface facilities and their associated infrastructure.

7.5.2 Natural Hazards

Natural conditions or events around the site could pose a hazard to the facility, and therefore are a factor in siting and design. These include meteorological, surface water, biological and fire hazards, and potential climate change impacts on these hazards (seismicity was discussed earlier in this report).

Based on available information from the Revell siting area, potential natural hazards that would require consideration include hot or cold temperatures, high winds, severe storms, excessive snow or ice, lightning, surface flooding and fires.

The most likely direct effect of these hazards would be loss of road access or loss of power to site. These would be addressed through normal engineering, design and operational procedures. For example, for loss of site power, the site would be equipped with stand-by generators. And since the used fuel does not require active water cooling by the time it is sent to the site, there is no need for backup power to support cooling.

Given the site is located within a forested area, one hazard of note is the risk from forest fires. This risk would be mitigated through design features such as a cleared area around the surface facility perimeter (fire break) and use of non-flammable materials (notably concrete) for the used fuel handling structures.

Another specific hazard is the risk of surface flooding under an extreme storm. This risk may be increased by climate change. A preliminary assessment of surface flooding hazard at the Revell site over the next century, including climate change, has indicated that there are multiple areas within the site where flooding would not occur even under an extreme storm (Rodriguez and Brown 2021). This is in part due to the nature of the topography, and since the Revell site is at the top of a watershed. The detailed design would avoid this risk through surface facility location, grading, shaft collar height, and stormwater management system.

7.5.3 Overburden

Geological mapping in the Revell batholith area indicates good bedrock exposure with generally low levels of overburden deposits. There are large outcrop areas and the overburden, where present, is generally thin. Average (estimated) overburden thickness around the edges of exposed bedrock outcrop varies between 0.3 m and 1 m.

Based on site investigations information to date, there is high confidence that the overburden conditions will not adversely impact construction of the repository. Additional geotechnical work during detailed site characterization will inform the level of effort regarding site grading, cut and fill, and aggregate requirements; however, these are all conventional construction challenges with solutions that do not affect overall safety and performance of the facility.

7.5.4 Host Rock Strength and Bedrock Stresses

As noted in Section 3.5, while there are no direct bedrock stress measurements at this time, borehole breakout data suggests that the orientations of the maximum horizontal stresses follow the general trend in the Canadian Shield. In situ stress measurements would be conducted as part of detailed site characterization. The underground layout will align the room and panel orientations taking this into account to optimize room stability.

Additionally, based on the rock strength as noted in Section 3.5, plus Canadian mining experience and also the experience from the AECL Underground Research Laboratory at Pinawa, Manitoba in the Canadian Shield, there is high confidence that both the strength of the rock and bedrock stresses would allow the safe excavation, construction, operation, and closure of the deep geological repository.

7.5.5 Mitigating Repository-Induced Effects

The geology at the Revell Site is favourable for the repository as discussed in prior sections. However, the presence of the underground repository will affect the rock. Therefore, the design, construction and operation take this into consideration and adopt various mitigations to preserve and work with the favourable rock features. These include:

- Placing the central service area and shafts away from the placement rooms;
- Excavation method optimized to minimize rock damage;
- Spacing out the placement rooms to limit temperature and rock stress;
- Aligning the rooms with the principal rock stresses;
- Temperature limits on the containers, which also limit the rock temperature;
- Staged construction, so that rooms are not empty for long periods;
- Backfilling and sealing rooms once containers are placed to minimize exposure of the rock to air;
- Minimizing and/or removing trace materials during construction and operations that might interact with the barriers; and
- Backfilling and sealing access tunnels, boreholes and shafts at closure.

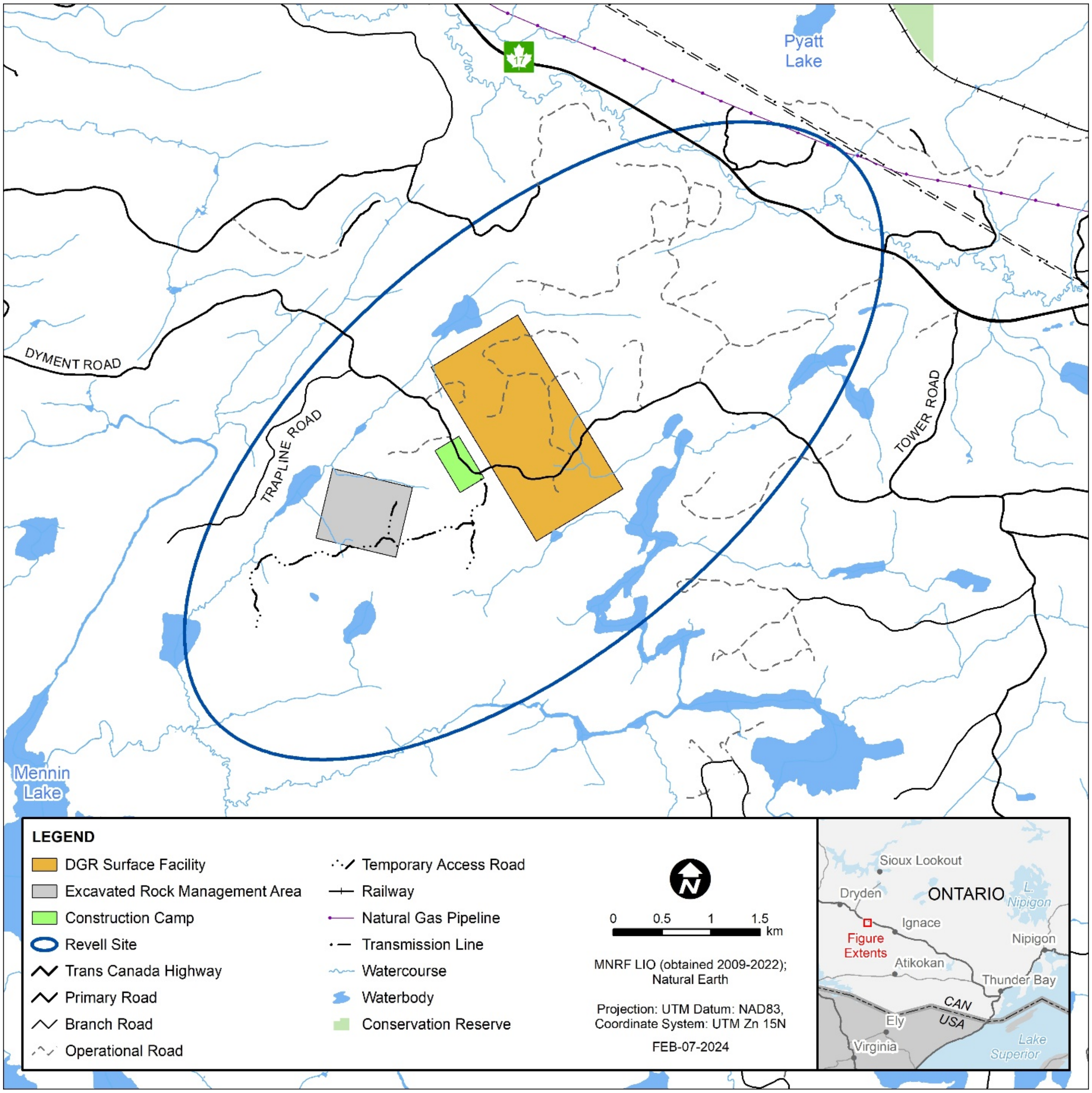

Figure 7.20: Conceptual locations for surface facilities and excavated rock management area, showing proximity to highway, natural gas pipeline and transmission line.

8. TRANSPORTATION

The repository site needs to allow the safe and secure transportation of used fuel from storage sites. The NWMO will need to demonstrate that the repository is located in an area that:

1. is amenable to the safe transportation of used nuclear fuel.

2. allows appropriate security and emergency response measures during operation and transportation of the used nuclear fuel.

The following sections elaborate on these key considerations for confidence in the transportation system.

For more information on the conceptual transportation system and plan, see NWMO's *Transportation System Conceptual Design Report* (NWMO 2021b) and *Preliminary Transportation Plan* (NWMO 2021c).

8.1 Developing a Safe Transportation System

8.1.1 Transportation System Overview

Used fuel is presently stored in interim facilities at or near reactor sites. This fuel will be transferred on-site from interim storage into certified transportation packages, and then brought to the repository site. Once at the repository site, the transport packages will be unloaded, checked, and then returned to pick up more used fuel.

The reference transportation system will operate for approximately 50 years. On an annual basis there will be around 650 shipments, which is about 2 to 3 packages per day on average. The number of daily shipments vary as the transportation system is designed to accommodate schedule variance due to weather, temporary road traffic and closures, unplanned maintenance, etc. The NWMO will not transport used fuel if conditions are not suitable.

8.1.2 Transportation Packages

Safety of transporting used nuclear fuel begins with transportation package design.

Transportation of used nuclear fuel will occur in a transportation package that adheres to stringent Canadian regulations and international standards. Used nuclear fuel transportation packages are designed and tested to ensure protection of people and the environment during normal operations, as well as during accident conditions.

The Canadian Nuclear Safety Commission (CNSC) is responsible for evaluating transportation packages and certifying designs. Before a transportation package can be used in Canada, the design must be certified by the CNSC to meet regulatory requirements, which incorporate international safety standards. The requirements include tests designed to demonstrate the ability of the package to withstand severe impact, fire, and water immersion. These are extreme tests to demonstrate the durability of the packages.

The specific tests include:

1. 9-m free drop test onto a flat, unyielding surface;
2. 1-m free drop puncture test onto a rigid spike of 15 cm diameter and 20 cm length;
3. Thermal test of a fully engulfing fire for 30 minutes at approximately 800°C; and
4. Immersion tests of 8 hours at 15 metres and 1 hour at 200 m.

Also, the certification requires that the drop tests be completed in sequence followed by the fire test on the same package. This is to emulate real world vehicle accidents.

The 9-metre free-drop test is a severe test compared to real world accidents. Although the speed of the package at impact can be much higher in real world accidents, the peak loads on the package during this test are many times higher than those experienced when a train travelling at 160 kilometres an hour collides with a transportation package. This is predominantly due to the use of rigid, unyielding target in the free-drop; a detailed analysis and explanation is provided in the NWMO technical report (Easton 2014).

In order to meet these tests, the transportation package designs typically feature thick body and lids. Packages are closed using seals and several large, highly torqued bolts or a welded closure. The closure area is further protected by an impact limiter, which effectively acts as a shock absorber in the event of impact and heat shield in the event of fire. An example certified package for CANDU used fuel, the Used Fuel Transportation Package (UFTP), is illustrated in Figure 8.1 and its characteristics are noted in Table 8.1.

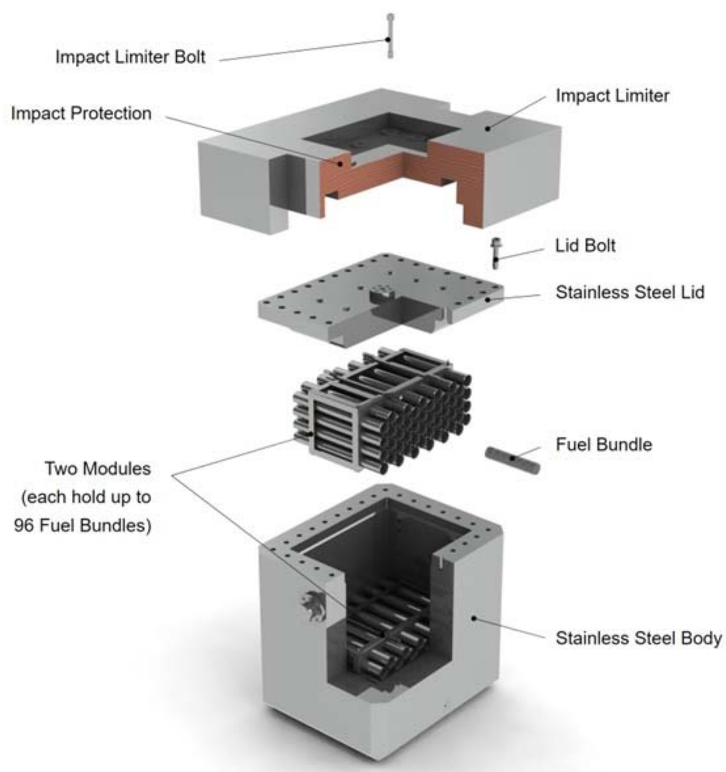

Figure 8.1: Illustration of Used Fuel Transportation Package (UFTP). It is a stainless-steel package with walls nearly 30 centimetres thick.

Table 8.1: Used Fuel Transportation Package Characteristics

	Used Fuel Transportation Package (UFTP)	Basket Transportation Package (BTP)[1]	Dry Storage Container Transportation Package (DSC-TP)[2]
Contents	192 used fuel bundles (2 rectangular modules, each holding 96 bundles)	120 used fuel bundles (2 cylindrical fuel baskets, each holding 60 bundles)	384 used fuel bundles (4 rectangular modules, each holding 96 bundles)
Approximate Assembled Dimensions	Length = 2.4m Width = 2.0m Height = 2.2m	Length = 2.3m Width = 2.3m Height = 2.5m	Length = 3.7m Width = 3.4m Height = 6.0m
Approximate Loaded Weight	35 tonnes	28 tonnes	100 tonnes

1: The BTP (currently under development) is a package for transporting cylinder fuel baskets (e.g., Gentilly-2 Quebec and Point Lepreau New Brunswick nuclear generating stations).
2: The DSC-TP is the transportation package configuration of the OPG Dry Storage Container (DSC). This package is part of the road/rail combination mode used fuel transportation system; on roadways it would be considered a superload. It is not used in the proposed reference transportation system.
* See references (NWMO 2021b, 2021c) for more information on these packages.

Package certification can be done via physical testing of scaled prototypes and/or computer modeling. The Used Fuel Transportation Package was designed and tested in the 1980s as shown in Figure 8.2. The package meets all regulatory requirements and is currently certified for use.

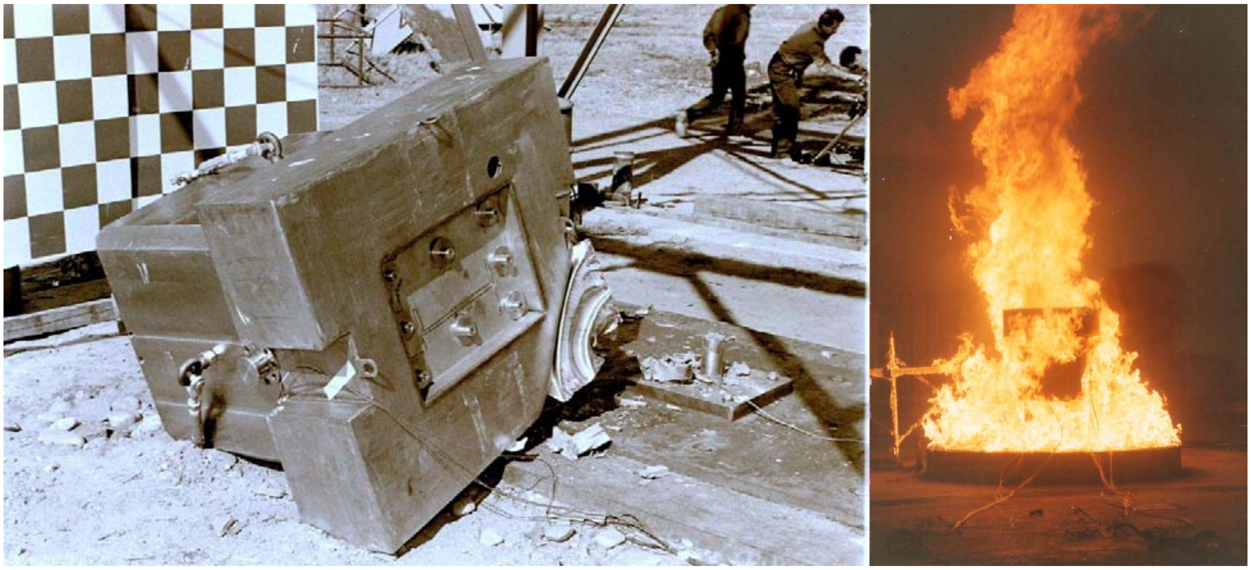

Figure 8.2: Half-Scale Used Fuel Transportation Package: (Left) after certification drop test; and (Right) during post-certification fire testing.

Figure 8.3: Photos from "Operation Smash Hit". A used fuel transportation package was tested by direct collision with train traveling at 160 km/h. (Left) Train just before collision, (Right) dented but intact package among wreckage.

Several countries have conducted additional testing to demonstrate the robustness of used fuel transportation packages. For example, in the United Kingdom, a test known as "Operation smash hit" had a locomotive and three train cars travelling at approximately 160 km/h purposely collide into a used fuel transportation package as shown in Figure 8.3. The package did not breach and there was only surficial damage. Videos of this test and other transportation package testing are readily available online (Cooperail 2015).

8.1.3 Transportation Modes

The NWMO is current investigating two potential transportation system designs using road and rail, as shown graphically in Figure 8.4:

1. All road transportation system
2. Road/rail combination transportation system

The all-road transportation system makes use of transportation packages that are of a size and weight suitable for transport over existing highway networks using tractor-trailers satisfying provincial road restrictions (i.e., not requiring oversize / overwidth permits, "conventional" road transport). Road transportation provides more flexibility in terms of scheduling and routing. The specific routes will be selected for each shipment based on conditions at that time, such as road construction, weather and security.

An all-rail option is not viable. Some of the existing interim used fuel storage sites (i.e., nuclear generating stations) no longer have functioning rail lines within a suitable distance or sufficient used fuel quantities to make rail practical. In these cases, a road/rail combination system may be possible depending on the interim storage site.

Such a combination system would require an **intermodal facility** – a facility to transfer transportation packages onto a tractor-trailer or on to a train. Additionally, some preferred packaging options would classify as a superload shipment. Superloads are heavy haul shipments that require special permits to transport because of their weight and/or size; for example, the dry storage container transportation package (DSC-TP) described in Table 8.1.

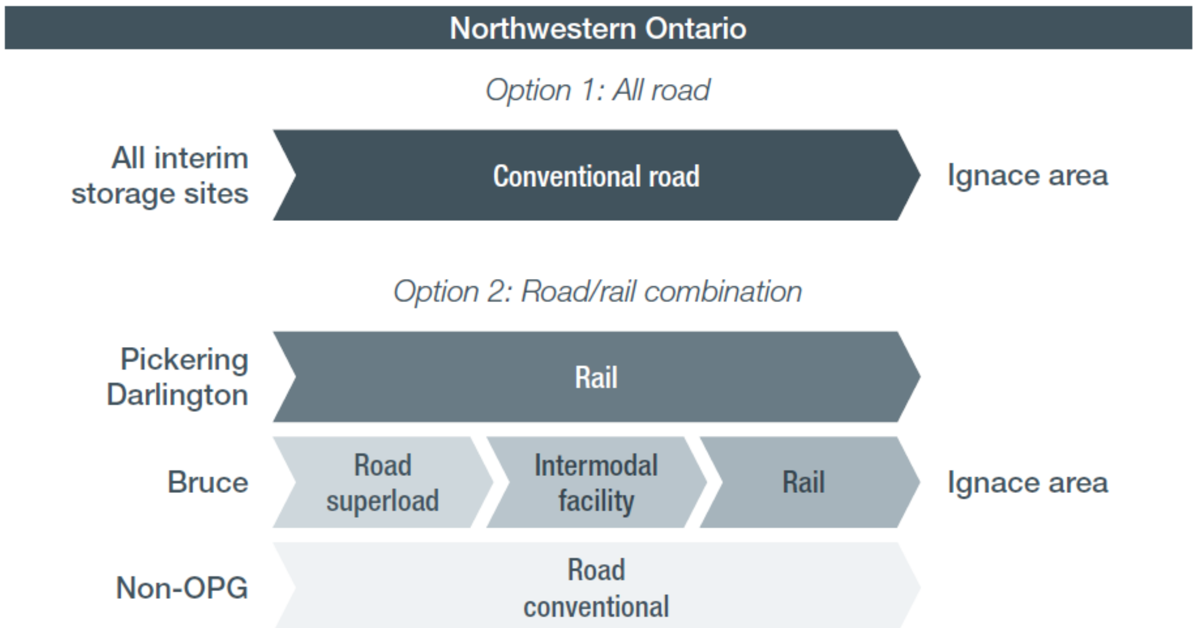

Figure 8.4: Transportation systems under consideration for the Revell Site

Conceptual designs of the all-road and road/rail systems were prepared for the Revell site and the technical feasibility of these systems assessed internally (NWMO 2021b).

The preliminary assessments considered potential routes; infrastructure (transportation and facility); equipment (transportation packages, conveyances, escort vehicles, communication equipment, emergency response and recovery equipment); logistics (shipping schedule) and operational activities required for transport of used fuel.

The potential repository area at the Revell Site is located close to existing road and rail infrastructure; specifically, within 10 km of the Trans-Canada Highway and the Canadian Pacific rail line (see Figure 7.20).

For both of the transportation systems above, the development of short connections from these main routes to the Revell site would be required (i.e., site access road / rail spur).

For the road/rail transportation system, an intermodal facility would be required near the existing GEXR rail line in southern Ontario to support transport from the Bruce Nuclear site, as well as, additional spur lines at OPG interim storage facilities. A conceptual intermodal facility is shown in Figure 8.5.

The NWMO considers both road and road/rail transportation systems to be technically feasible for the Revell Site; however, the road/rail combination system requires more infrastructure, facilities, and package handling operations. At this time, the NWMO reference Used Fuel Transportation System for the Revell Site is the all-road system. The all-road transportation system uses existing highway networks for the journey, provides more flexibility in terms of scheduling and routing, and avoids the need for intermodal facilities and superload shipments. Further assessment of the potential routes and infrastructure upgrade will be required after the site has been selected and detailed routing assessments have been completed.

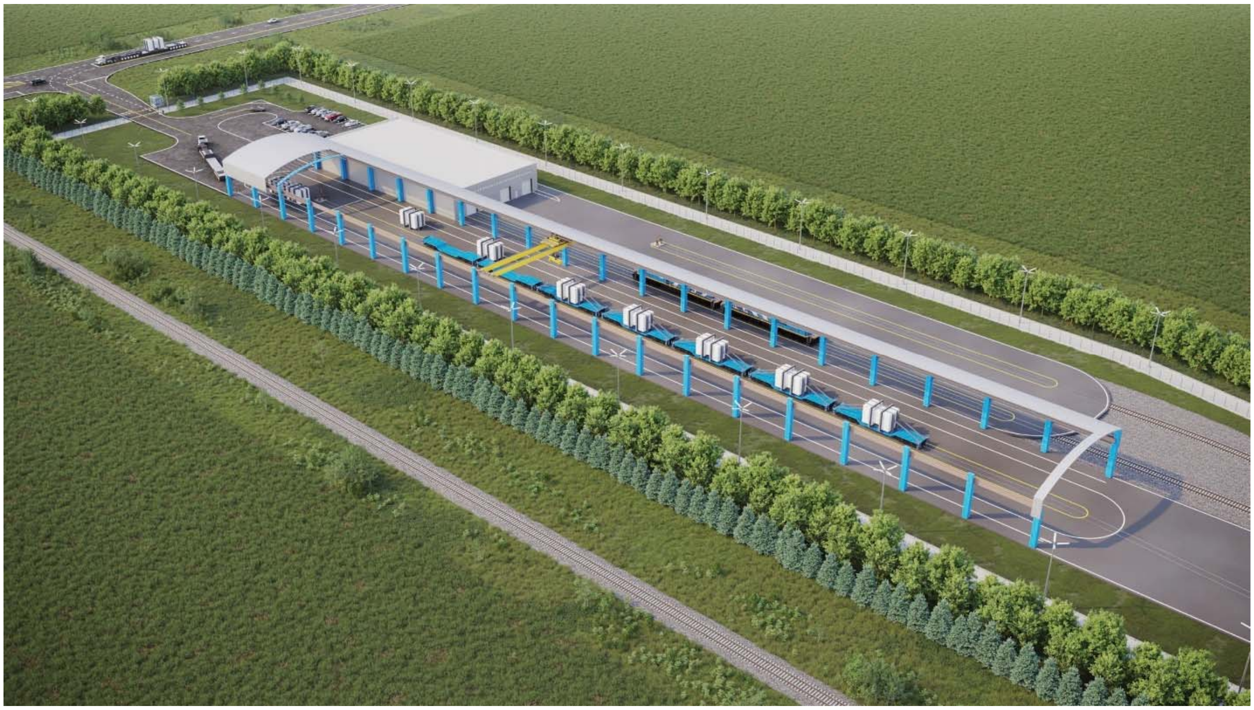

Figure 8.5: Conceptual Used Fuel Transportation System Intermodal Facility to transfer packages from rail to road modes.

8.2 Security and Emergency Response

The NWMO's transportation program will need to meet the CNSC's and Transport Canada's regulatory requirements. These regulations cover the transportation package certification, operational and radiological safety, security provisions, and emergency response.

The following sections describe the security and emergency response aspects of the transportation program.

Based on the information to date, the Revell Site does not present any barriers that prevent effective security and emergency response planning and protocols for the operational phase. Similar plans have been successfully applied nationally and internationally on used fuel shipments for over 50 years (US DOE 2016). As a result, there is high confidence that a safe and secure transportation system can be designed and operated.

8.2.1 Security

A licence from the CNSC is required to transport used nuclear fuel. As part of the licence application, a Transportation Security Plan must be developed that includes:

- Threat assessment that looks at the nature, likelihood and consequences of acts or events that may place prescribed information or the used fuel bundles at risk, along with corresponding mitigation measures, including emergency response;
- Communication arrangements;
- Proposed security measures;
- Arrangements with response forces; including provisions for advanced notification of shipment and contacting the appropriate response forces during shipment;
- Provisions for the support of response forces along the transport route;
- Planned and alternate routes;
- Contingency arrangements to address such events as a mechanical breakdown of a transport or escort vehicle, or failure of a shipment to arrive at its destination at the expected time; and
- Procedures to be followed during an unscheduled stop or unscheduled delay during transport.

To protect the safety and security of the shipments the regulations mandate that the Transportation Security Plan is prescribed information and cannot be made publicly accessible.

In addition to the security plan, the shipments will be accompanied by one or more escorts. Their responsibilities would involve:

- Conducting searches of persons, materials, vehicles, as needed;
- Remaining in frequent contact with the shipper, receiver, local authorities, and response forces along the transport route;
- Inspecting for security breaches and vulnerabilities, and ensuring the secure storage of any transport equipment; and
- Responding to and assessing incidents and events.

Finally, communication, tracking, and other security technology are used to ensure the shipments are completed safety and securely. Drivers and escorts will communicate with a central Transportation Communication and Control Centre, which monitors and tracks all shipments and acts a single point of contact for all agencies involved. The technologies involved include:

- Communication equipment including combination of encrypted satellite telephone/communications, encrypted cellular telephone, and privately licensed CB radio frequencies.
- GPS tracking systems to monitor the location of the tractor-trailers, transportation packages, and escorts during the shipments.
- Anti-theft electronic immobilizer systems installed on the tractor-trailers, which allow remote disabling of the vehicle and may include biometric scanners for operation (e.g., handprint).

8.2.2 Emergency Response

In Canada, the emergency management community has adopted a standard approach for responding to incidents. Federal, provincial and local governments use a comprehensive approach to emergency management, which includes having in place measures for prevention, mitigation, preparedness, and response and restoration activities for all modes of transportation.

The NWMO will develop and provide a Transportation Emergency Response Plan to the Canadian regulatory agencies to demonstrate that appropriate emergency measures are in place. The plan will ensure co-ordination among the NWMO, provincial and local first responders, as well as federal agencies. It will also describe relevant agreements with other nuclear facilities for response assistance. NWMO will work in collaboration with provincial and local governments to ensure training and equipment for first responders meet required standards along the transportation route.

The emergency response plan may include, but is not limited to the following:

- Description of the emergency response organization and external agencies, as well as their roles, responsibilities, capabilities, and duties, and how they will work together;
- Agreements on assistance with other facilities and/or other organizations;
- Plans for mobilizing and deploying resources for response;
- Description of roles and responsibilities (e.g., driver, escort, NWMO transportation command centre staff, first on the scene team, response team, recovery team);
- Training and qualification requirements, as well as drills and joint exercises; and
- Communication protocols, as well as procedures for alerting and notifying key organizations and personnel, as well as the public.

As an additional support, Transport Canada operates Canadian Transport Emergency Centre (CANUTEC) – a national advisory service that provides immediate assistance to emergency response personnel in handling dangerous goods emergencies on a 24/7 basis. The emergency centre is staffed by bilingual scientists specializing in chemistry or a related field and trained in emergency response. CANUTEC would also have access to technical advisors from the shipment-based Emergency Response Assistance Plan.

9. NATURAL ANALOGUES FOR BARRIER DURABILITY

The repository will need to be effective for very long times. In addition to the stability of the geosphere, the long-term stability of the engineered barrier materials is important. These materials have been selected based in part on the known durability of similar natural materials under deep geological conditions.

In particular, the Cigar Lake uranium ore body in Saskatchewan is a natural analogue for the repository (see Figure 9.1). Geological evidence from Cigar Lake indicates that the uraninite ore, a natural uranium oxide, remained stable underground for over 1.3 billion years. The combination of uranium oxide ore, surrounded by natural clay, in a deep geological setting was effective in containing the uranium such that there was no indication of the ore deposit at the surface (Cramer and Smellie 1994). In a repository, the similar stability of the uranium oxide used fuel will also help ensure long-term containment of the radionuclides in the used fuel.

Similarly, the stability of copper can be inferred from the existence of natural copper deposits. Notable examples are the natural copper plates found in the Keweenaw Peninsula in northern Michigan (Figure 9.2) and in the Permian Littleham Mudstone in southwest England. The existence of these long-lived deposits shows that copper and bentonite clay can remain stable for long periods under conditions not very different to those expected in a repository.

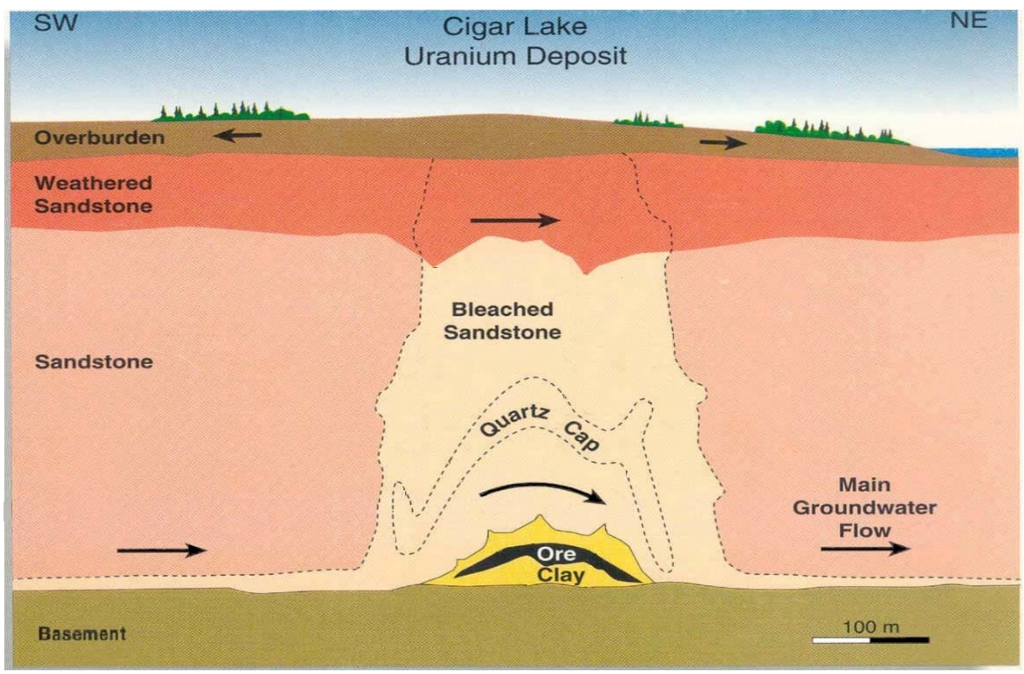

Figure 9.1: Cross-section of the Cigar Lake uranium ore body in Saskatchewan (adapted from Cramer and Smellie 1994). The uranium ore, surrounded by a clay layer at 430 m depth, has remained isolated from the surface environment for over 1.3 billion years.

There are numerous other natural analogues that provide evidence for the long-term behavior of the materials in the repository. Table 9.1 summarizes several useful analogs.

Table 9.1: Selected natural analogue studies

NATURAL ANALOGUE	PHENOMENA/PROCESSES
Uranium dioxide (fuel) behaviour	
Cigar Lake uranium ore body, Saskatchewan, Canada	Stability of uranium oxide over 1.3 billion years underground. (Cramer and Smellie 1994).
Oklo natural reactor, Gabon, Africa	Natural nuclear reactor that operated underground for a few hundred thousand years about 2 billion years ago. Illustrates slow transport of some radionuclides in a geological setting.
Copper and copper-iron behaviour	
Natural copper, Keweenaw Peninsula, Lake Superior, USA	Natural copper ore formed 1 billion years go and remained stable, illustrating durability of copper under underground conditions.
Natural copper, Littleham Cove, England	Natural copper plates formed about 200 million years ago, and preserved in compacted clay. Illustrates long-term stability of copper in clays (SKB 2000).
Kronan cannon, Sweden	Bronze (copper alloy) cannon buried under sea mud for 300 years. Illustrates durability of copper under anoxic conditions.
Inchtuthill nails, Scotland	Buried iron nails from Romans. Illustrates slow iron corrosion in anoxic conditions.
Clay behaviour	
Wyoming bentonite, USA	Large deposits of bentonite clay formed from volcanic ash from 95 million years ago, illustrating durability of bentonite clay.
Dunnarobba forest, Italy	Wood tree stumps preserved in clay 2 million years ago. Illustrates ability of clay to preserve materials, in part through suppressing microbial activity.
Avonlea bentonite, Saskatchewan	Chemical and mineralogical stability of bentonite over 75 million years
Cement and concrete behaviour	
Hadrian's Wall, Great Britain	A simple form of cement was used in the walls 1900 years ago. Illustrates cement durability.
Maqarin, Jordan	Interaction of 2-million-year-old natural cements with surrounding rock. Illustrates scientific understanding of the long-term effects is consistent with real site behaviour.

Figure 9.2: Natural copper sheet from White Pine Mine, Keweenaw Peninsula, Michigan, USA (on display at Royal Ontario Museum). This copper shape is because it was extracted by blasting in the mine. The copper sheet is about 1 billion years old.

10. SAFETY ASSESSMENT

10.1 Context

A safety assessment is performed to confirm that the repository will meet regulatory safety criteria. The safety assessment does this in part through demonstrating that under many scenarios, both likely and unlikely, the potential maximum dose to a family living on or near the repository would meet safety criteria and be well below regulatory limits.

The safety assessment is a systematic quantitative analysis. The basis for the assessment is described in Canadian regulatory documents (notably REGDOC 2.4.4 and REGDOC-2.11.1, CNSC 2021a,b; CNSC 2022), which are informed by international guidance (e.g., IAEA 2011a,b). The safety assessment is ultimately evaluated by the Canadian nuclear regulator during the federal Impact Assessment and CNSC licensing processes.

Prior to the present evaluation of a repository on the Revell Site, seven post-closure safety assessment studies were carried out in Canada for hypothetical sites. Two of these assessments (AECL 1994, Wikjord et al. 1996) were reviewed as part of the federal 1998 Environmental Assessment on the concept of deep geological disposal of nuclear fuel waste, the Seaborn Panel (CEAA 1998). Subsequent generic assessments were conducted to develop and document understanding of the key factors in such safety cases. The most recent Canadian study for a crystalline rock site was called the Sixth Case Study (NWMO 2017).

Safety assessments of other sites have been prepared and accepted as part of the licensing process for proposed repositories in Finland (Posiva 2007), Sweden (SKB 2011) and France (Andra 2005). Safety assessments have also been published in other countries, including United Kingdom (RWM 2016) and Switzerland (Nagra 2002).

Although the geological environment and design details varied from study to study, these studies found that geological disposal in a suitable rock could protect humans and the environment from the long-term hazards of used nuclear fuel. These and similar studies have supported the plans by countries with major nuclear power programs to manage their used fuel or high-level radioactive wastes in a deep geological repository (see Section 11). The NWMO is now building on these studies to develop an assessment specific to the Revell Site.

10.2 Assessment Basis

The assessment starts with the understanding of the used fuel itself, in terms of amounts and characteristics, including subcriticality. This is considered along with the information developed through the site characterization and environmental baseline programs, and the development of the engineering design for the site. As more information becomes available, and as part of the licensing process, the safety assessment is progressively iterated to provide a more detailed assessment.

As noted in Section 2, the effects of nuclear radiation are described as the radiation dose. The results of the safety assessment are based on this concept. For people, radiation dose is reported here in units of millisieverts (mSv). People are constantly exposed to nuclear radiation from natural sources around us (see also Section 2). Figure 10.1 illustrates doses typically received by Canadians from a variety of sources.

The average Canadian receives a natural background dose of about 1.8 mSv each year from natural sources (Grasty and LaMarre 2004). This radiation varies by location; for example, it is about 1.5 mSv in Toronto and about 4.0 mSv in Winnipeg.

People also are exposed to radiation from human activities (RI 2022, CNSC 2023a). Many of these are for medical purposes such as dental x-rays or screening mammogram. People may also be exposed through flying, due to the higher elevation. There is no difference between the effects caused by natural or human-made radiation for the same effective dose.

In Canada, the nuclear regulator CNSC has set regulatory limits on the additional dose that the public and the nuclear energy workers can receive from the nuclear facilities. The limits are set at 1 mSv per year above background for members of the public, and 50 mSv per year for nuclear energy workers (CNSC 2000). In practice, the regulators and facility operators follow the principle of As Low As Reasonably Achievable (ALARA), and actual doses are much less than these regulatory limits.

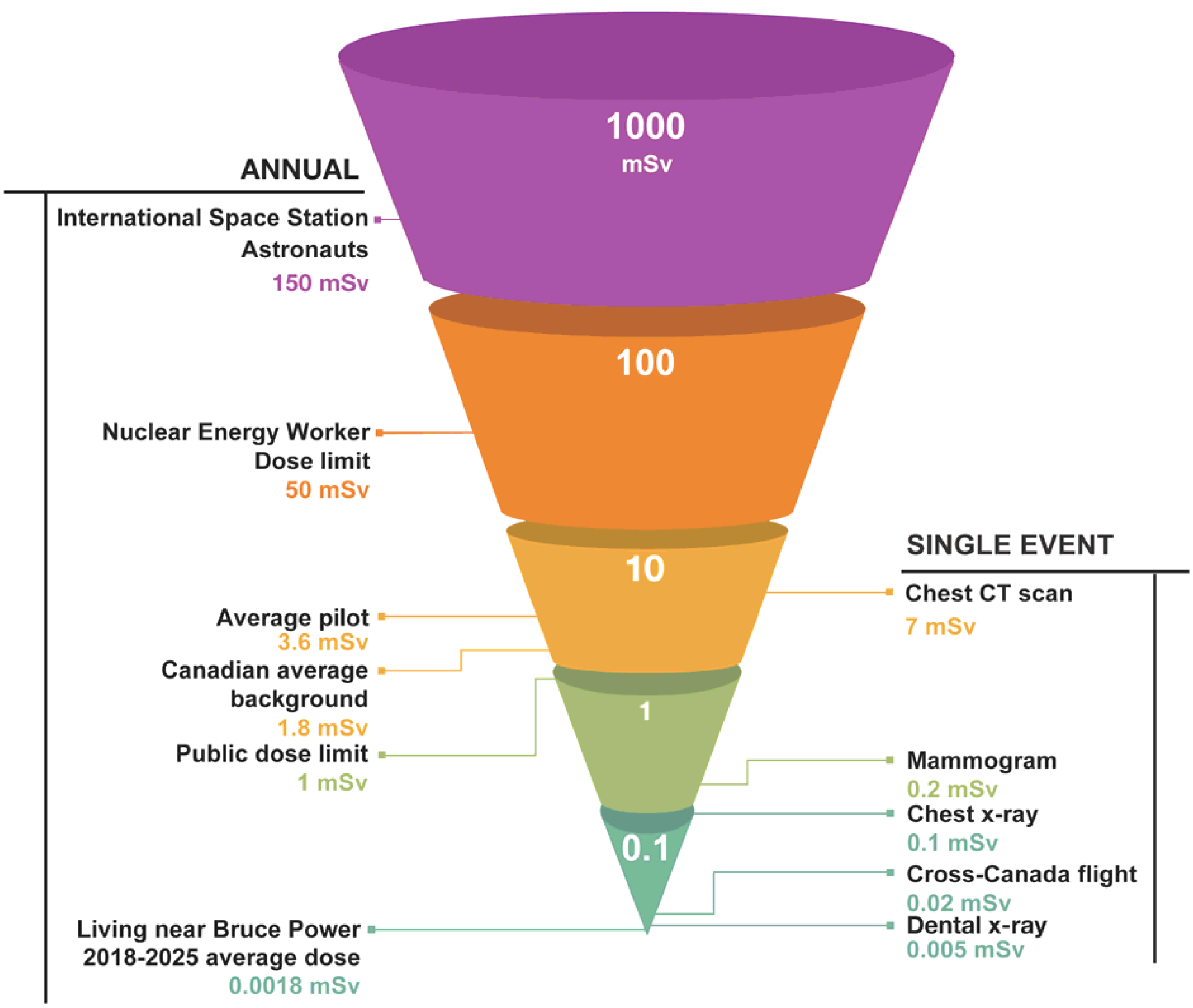

Figure 10.1: Typical radiation doses from various sources.

The assessment also evaluates the potential impacts in the environment around the site, including water. It assesses the implications by considering the effects on representative biota (animals and plants) living in the area. The dose impacts on biota are evaluated using different units, milliGrays (mGy), using national and international reference criteria.

10.3 Pre-closure safety: Handling used nuclear fuel safely

The pre-closure period covers the handling of used nuclear fuel at surface and placement in the underground repository, until the surface facilities have been decommissioned and the underground repository has been sealed and closed. The repository includes surface facilities for fuel handling and the underground facilities.

During this period, there is no conditioning or treatment of the fuel itself. The fuel is handled in air, not water, as it does not need much cooling. The fuel handling is done remotely using automated or remote handling equipment. The handling is conducted at surface in a robust facility, with standard shielding, treatment and filtration systems. Once underground, the fuel is protected by the container, the engineered barriers and the rock.

The pre-closure safety assessment considers the range of possible repository performance, then estimate how this varying performance might affect the public, workers, and the environment. The assessments considers both normal operations and unlikely scenarios, such as an accident or severe weather event.

10.3.1 Normal Operations

Fuel bundles will remain sealed during the routine handling of used fuel as shown in Figure 7.19. However, the safety assessment considers the possibility of small releases from the fuel during normal operations within the facility. This could be residual gamma radiation penetrating beyond the fuel, and from small levels of gas or loose particulates that may be released from the fuel bundles during handling. It also considers radon, which is naturally produced from the small amount of uranium and thorium present in the rock, and released from the rock brought to surface (NWMO 2020).

The safety assessment considers an imaginary person assumed to be living year-round at the location of greatest potential exposure - usually the facility fence line, breathing the air, drinking the water, and eating food assumed grown at this location. We calculate the maximum potential dose to that person. This is a conservative assumption for safety assessment and licensing purposes.

The assessment also considers more realistic lifestyles approximately representing people that might live near the facility, say about 1 km from the surface facilities, to provide further insight into the repository safety.

It is important to note that the facility would be monitored within the facility, at the fence line, and in the surrounding area. This monitoring is standard practice at any nuclear facility in Canada. Both the NWMO as the facility operator, and the CNSC as the federal regulatory agency, would operate their own monitoring stations. The results of this monitoring will be reported publicly. Examples of this reporting around existing nuclear stations can be found in Bruce Power (2023) and CNSC (2023b).

10.3.2 Accidents

Along with assessing the potential impacts of normal operations, it is also important to plan for uncertainties. We assess the consequences of uncertainties by looking at hazards both within the repository facilities and outside of them. The assessment considers:

> Accidents - A range of potential accident scenarios is considered, including accidents with a very low likelihood of occurring. Identified accidents include equipment failure leading to the drop of fuel bundles in the surface facility.
>
> External hazards - This includes a range of outside hazards, such as flooding or fire. These are characterized specific to the siting area to ensure that the repository facility is designed to withstand the hazards (see Section 7.4.2).

For each accident scenario,

1. We estimate the amount of material that could be released during the accident scenario. This takes into consideration the accident type (e.g., a dropped fuel bundle or fire) and whether the fuel is inside of a package which may provide some protection.

2. We assume that if radioactive material is released, it could travel through the air to reach a member of the public. The assessment considers an imaginary person living at the location of greatest potential exposure, such as the facility fence line.

3. We estimate the dose to that imaginary member of the public and compare the calculated dose to the public-dose limits to determine safety. The potential dose to real people would be lower.

The results of our preliminary assessment are illustrated in Figure 10.2, which shows calculated doses for normal operations and potential accidents for an imaginary person assumed to be at the locations of peak exposure (i.e., living at or near the facility fence line). The dose magnitudes are illustrated as volumes, using the Canadian natural background dose as a reference.

10.3.3 Preliminary Results

Overall, the preliminary pre-closure safety assessment shows that used fuel handling can be performed safely. During normal operations, the dose to members of the public are below regulatory limits and well below their dose from natural sources. Even during potential accident scenarios, the repository would protect people.

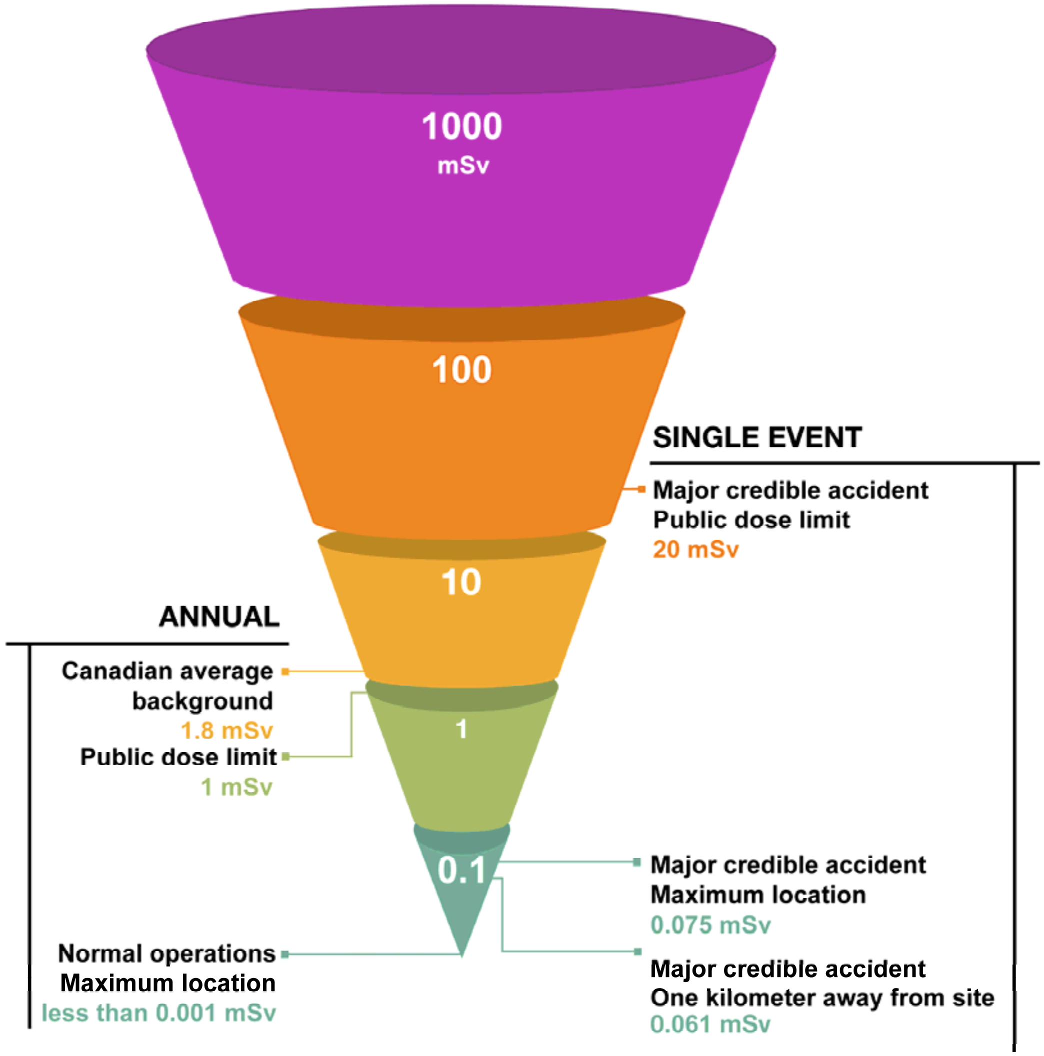

Figure 10.2: Illustration of potential pre-closure peak dose in comparison with natural background and regulatory limits.

10.4 Post-Closure Safety: Ensuring the site remains safe long term

The post-closure period covers the repository performance after the surface facilities have been decommissioned and the underground repository has been sealed and closed.

The post-closure safety assessment gauges the repository's future performance in part by considering a range of expected and unlikely scenarios, including illustrative "what if" scenarios. We estimate the potential consequences of those scenarios on future people and the environment.

The current preliminary analysis considers the underground repository is excavated at a depth of about 750 metres. The actual depth will be finalized based on more detailed site characterization.

10.4.1 Normal Evolution Scenarios

The normal evolution scenarios are those scenarios where the repository performs largely as expected, considering normal degradation processes and reasonable uncertainties.

The repository design is based on multiple barriers. It uses materials for which there are abundant natural examples (“natural analogues”, see Section 9) that have been stable and durable for millions of years – far longer than needed for the repository. The used fuel containers in particular are designed to remain intact for over one million years. They have the strength to carry the load of the rock overhead, plus a 3 km-thick glacier, and they are protected by a layer of corrosion-resistant copper.

In the post-closure phase, the site is assumed to remain under institutional controls for a period of time. These controls would be administered by a designated institution or authority and can include both active measures (such as monitoring and maintenance) and passive measures (such as land use restrictions, as well as measures taken to support societal memory). Such measures should prevent inappropriate land use, including drilling, deep excavation, or disruption of the shaft seals. It is assumed for safety assessment purposes that these institutional controls and societal memory would be effective for about 300 years; however, in practice they could be effective for much longer.

After the repository is sealed and closed, as designed, water will be unable to reach the used fuel. All potential contaminants are locked in and can never leave. There is zero impact.

To further assess the safety of the repository, we assume several used fuel containers would fail, and we estimate the potential consequence to people and the environment in such instances. These might be caused by local geological variability or local placement quality variations. These are not likely but possible. We assume that the containers would fail fully and completely, and that potential contaminants could leave the underground repository.

10.4.2 Alternative Scenarios

We also evaluate unlikely “disruptive” events, where a significant event occurs beyond our likely range of events. One possibility is a much larger future glaciation event. We also consider the unlikely scenario where all containers in one placement room fail, and further assume this failure would occur in the location with the greatest dose potential.

We also consider a “what if” scenario where all the used fuel containers fail at about the same time.

10.4.3 Preliminary Results

The post-closure safety assessment considers how any potential contaminants from the repository, regardless of amount, could get into shallow groundwater, surface waters, air, sediment and soil, and then look at their potential impact.

The assessment gauges impact in part by estimating the dose a future person could receive under a variety of post-closure scenarios, then comparing those against benchmarks such as the annual background dose from nature, 1.8 mSv/a (Canada average), and the Canadian regulatory public-dose limit of 1 mSv/a.

The dose received under different scenarios depends on a person's lifestyle; specifically, the relationships they have with their environment including through water and diet. Knowing this, we consider several local lifestyles in our safety assessment: town and rural residents, Indigenous lifestyles, and a hunter-gatherer. Each is based on different relationships with water and food.

Our preliminary post-closure assessment considers a future person with an "imaginary maximum" lifestyle, an entirely theoretical lifestyle designed to receive maximum potential exposure. For example, this person only drinks water from a deep well located wherever there is the greatest dose potential.

We also consider a range of representative biota (animals and plants) from the area, which all have unique relationships with the environment, including water.

The results of our preliminary assessment are illustrated in Figure 10.3, which shows calculated peak doses (after thousands of years) for different scenarios including "what if" all containers fail, for an imaginary person assumed to be living at the location of maximum exposure, and for a rural person living in the general vicinity of the site.

In all scenarios considered in our current preliminary assessment, the estimated impacts from the repository are well below the natural background and the regulatory dose limits.

This is true even if every container fails. The used fuel and the rock still provide a substantial barrier and will contain and isolate the radioactivity in the used fuel from people and the environment.

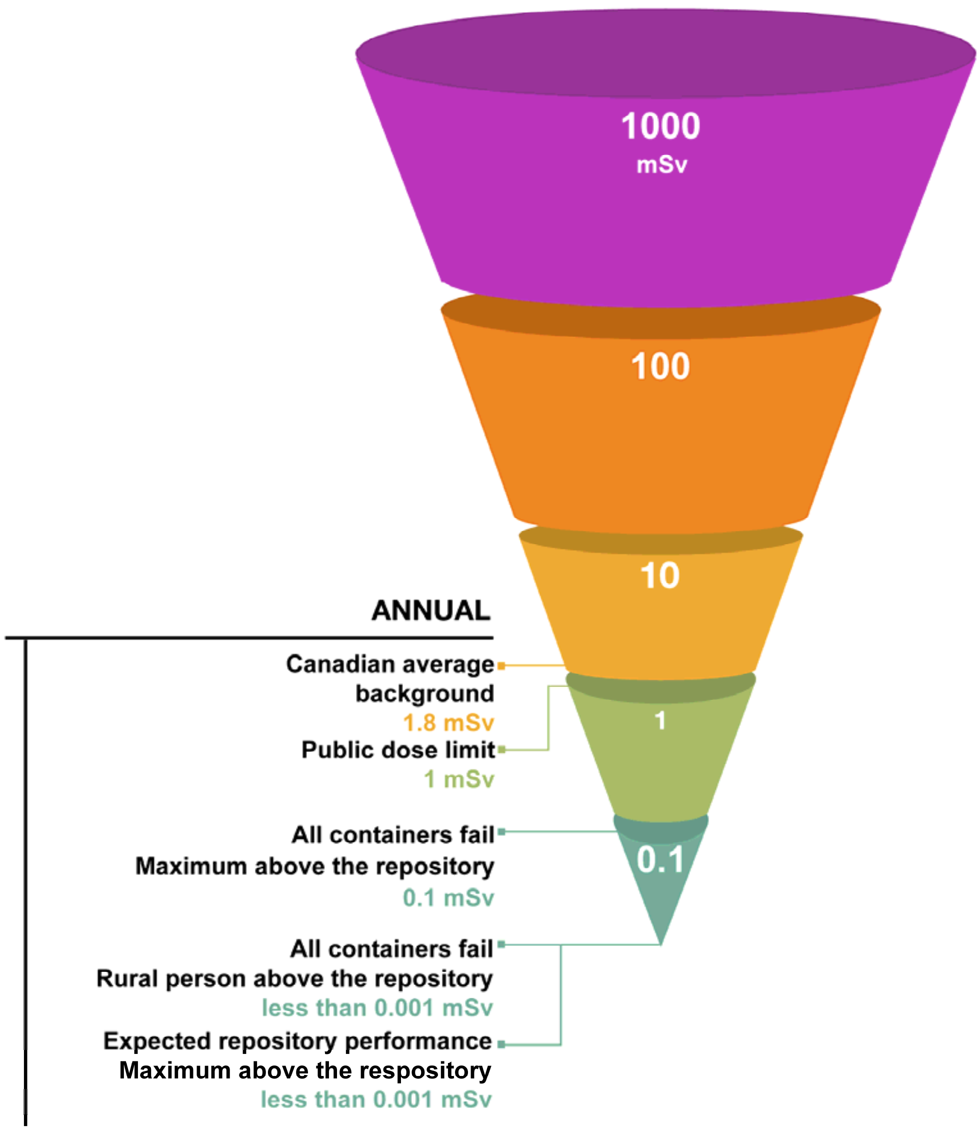

Figure 10.3: Illustration of potential post-closure peak dose in comparison with natural background and regulatory limits.

11. INTERNATIONAL CONSENSUS

Deep geological disposal is proposed internationally as the preferred long-term management approach for used nuclear fuel and other high-level radioactive waste. It has been adopted as the national plan in most countries with substantial nuclear power programs.

Geological disposal is backed by decades of worldwide research and development, including in crystalline, sedimentary and salt rocks. There have been a wide range of studies from laboratory experiments to major underground demonstration projects. Canada, in particular, conducted several major experiments at the AECL Underground Research Laboratory in Pinawa, Manitoba (Chandler 2003). Collectively, this worldwide experience provides assurance that this approach is supported by good scientific understanding (OECD 2020).

There are currently no operating underground repositories for used fuel and high-level wastes, but one is under construction and three are in licensing. Table 11.1 summarizes the status in various countries for used fuel disposal.

There are several operating underground repositories for low and intermediate-level radioactive wastes in other countries, including the US WIPP facility for transuranic wastes. There are also several near-surface disposal facilities in other countries for low-level radioactive wastes.

In Canada, the NWMO facility would be the only deep geological repository for used fuel. However, for clarity, the following other projects have or are being considered for nuclear wastes in Canada:

- A deep geological repository for Ontario Power Generation's (OPG) low and intermediate level radioactive waste was proposed at the Bruce nuclear site in the Municipality of Kincardine, Ontario. Environmental assessment hearings were completed in 2015, but the project was cancelled by OPG as it did not have the support of the local First Nation.

- A deep underground research laboratory was constructed near Pinawa, Manitoba, and operated from about 1980 to 2010 (Chandler 2003). Although the site information was used to support a federal environmental assessment review (AECL 1994), it was never intended as a repository. No wastes were placed in this site, and it has since been closed and decommissioned.

- A proposed near-surface disposal facility for low-level radioactive wastes at the Chalk River nuclear site is currently being evaluated through the Impact Assessment process (CNL 2021). A CNSC decision is expected in 2024.

- A surface disposal facility for historic low-level radioactive waste was completed in 2021 at Port Granby in Ontario. A similar facility is under construction at Port Hope in Ontario. (www.phai.ca)

Table 11.1: Repository plans for used fuel and high-level waste in several countries

COUNTRY	FORM OF WASTE	ROCK TYPE	DEPTH	CONTAINER CONCEPT	LOCATION	SCHEDULE
Finland	Used fuel	Crystalline rock (granite)	~450 m	Copper shell and cast iron structure; surrounded by bentonite clay	Olkiluoto site on southwest coast	Construction in progress. Operating licence application in 2021.
Sweden	Used fuel	Crystalline rock (granite)	470 m	Copper shell and cast iron structure; surrounded by bentonite clay	Forsmark site on east coast	Construction licence approval in 2022
France	Vitrified HLW, used fuel, long-lived ILW	Clay rock	~500 m	Steel containers; placed within concrete tunnels	Meuse/Haute-Marne area in east-central France	Construction licence application in 2023
Switzerland	Vitrified HLW and used fuel	Clay rock	400 – 1000 m	Steel canister (copper coating under evaluation) surrounded by bentonite clay	Nördlich Lägern area in northern Switzerland	Site selected in 2022
China	Vitrified HLW, used fuel	TBD	TBD	TBD	Three candidate sites in Gansu province	Constructing underground research lab at one site. Site selection in 2020s.
Russia	HLW	Crystalline rock	TBD	TBD	Zhelezno-gorsk in Krasnoyarsk Territory, Siberia	Site approved in 2016; constructing underground research lab at site
UK	Vitrified HLW, used fuel	TBD	TBD	TBD	TBD	Siting process underway; several communities under consideration
Germany	Vitrified HLW, used fuel	Clay, crystalline and salt rock options	TBD	TBD	TBD	Starting siting process
Japan	Vitrified HLW	TBD	TBD	TBD	TBD	Siting process underway
USA	Used fuel from power reactors and navy program, vitrified HLW	TBD	TBD	TBD	TBD	TBD. Licence application filed 2008 for Yucca Mtn but subsequently suspended

*TBD – To be decided, HLW – High-level waste, ILW – Intermediate-level waste

12. MONITORING

The site will be monitored for decades during site characterization, preparation, construction and operation, so there will be a substantial amount of information on the repository before a decision is made to close the repository.

General monitoring expectations are laid out in the International Atomic Energy Agency (IAEA) site-specific safety guide, "*Monitoring and surveillance of radioactive waste disposal facilities*" (IAEA 2014). International practice in repository monitoring is illustrated in reports from the Finnish repository site (e.g., Posiva 2012) and the Swedish repository site (e.g., Berglund and Lindborg 2017). The Canadian regulatory system also defines monitoring expectations for nuclear and other industrial facilities, for example, CSA (2015) and CNSC (2017). Environmental monitoring is standard practice at all nuclear facilities including uranium mines.

12.1.1 Site Selection and Site Characterization Phase

At the Revell Site, instrumentation to monitor pressures is in place for four boreholes. Nine microseismic stations have been installed within a 50 km radius of the site, allowing for monitoring of seismicity (i.e., earthquakes) down to magnitude one. In addition, a shallow groundwater monitoring network has been installed around the siting area and baseline environmental monitoring is underway. If this site is selected for detailed site characterization, additional monitoring installations would be completed at that time.

12.1.2 Site Preparation and Construction Phase

Monitoring of the environmental, geotechnical and geoscientific conditions during the shaft and repository level excavation will be used to confirm expectations from prior surface-based measurements, including directly informing the construction program (i.e., confirmation of room locations and orientations).

Tests on engineered barrier and repository operation topics will be conducted in the Underground Demonstration Facility (UDF), which would be constructed early in the excavation stage. Figure 12.1 is an illustration of the repository concept showing the underground demonstration areas.

The tests during this phase will include short-term tests that would inform the application for a licence to operate the facility, 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 container tests in a trial placement room. Monitoring equipment would be installed as part of these tests located within the central services area.

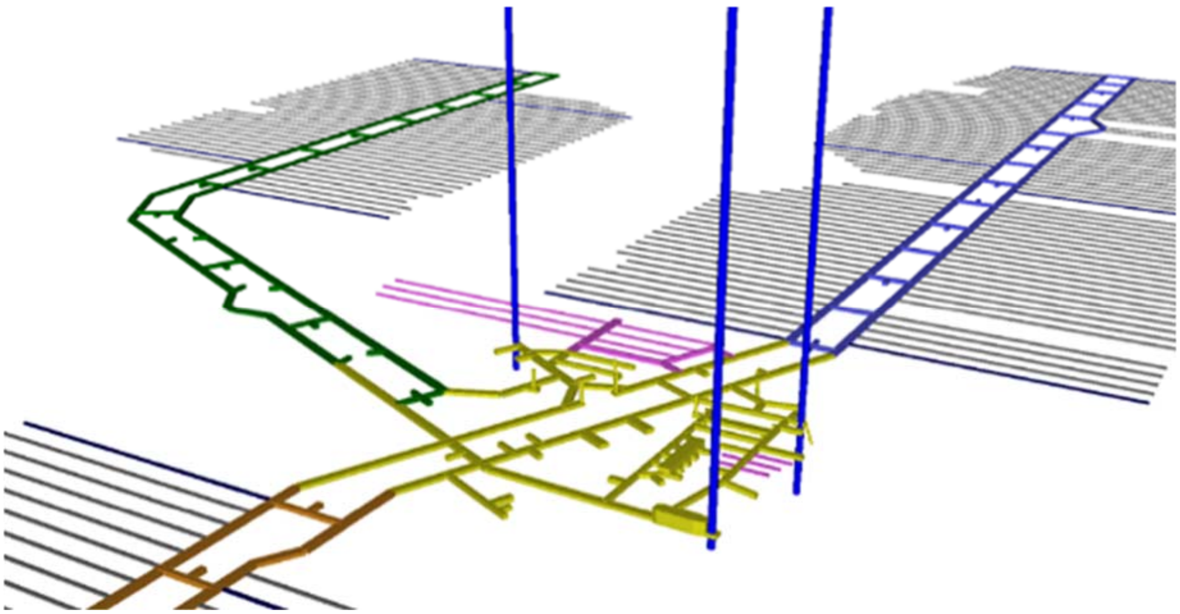

Figure 12.1: Illustration of centralized service area of repository showing the underground demonstration areas (highlighted in purple). (For illustration purposes only; does not reflect site-specific layout for Revell Site).

12.1.3 Operations, Monitoring and Closure Phase

The operations, monitoring, and closure phase will extend over a period of 100+ years. During this time, the monitoring of the environmental and geological conditions would continue.

Ongoing environmental monitoring will support the repository construction and operations, as well as confirm that the repository is not causing unanticipated effects on people or the environment, including water.

There are three general categories of monitoring that would occur during this time:

- Geological monitoring;
- Underground Demonstration Facility (UDF) tests; and
- Specialty borehole tests and monitoring.

The first category would include the continued monitoring of geological conditions including:

- Stress fields in the rock, and changes caused by excavation and heating;
- Groundwater pressure and chemistry, and changes caused by excavation and heating;
- Rock temperature, and changes caused by excavation, ventilation and heating; and
- Initiation, propagation and dilation of fractures, displacement of rock around openings.

This monitoring would be achieved by several methods including remote monitoring (e.g., acoustic emissions), tunnel monitoring (e.g., groundwater chemistry, temperature) and borehole monitoring (e.g., chemistry, radioactivity, porewater pressure, temperature). It will be used to verify that, at least at distances of tens of metres from the containers, conditions are as expected. All monitoring systems will be designed to ensure no impact to the functionality of the engineered barrier system and long-term safety of the repository.

The second category would include dedicated tests conducted within the UDF (or other niche 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 placement room tests.

In the demonstration tests, containers could be installed in a well-monitored environment similar to a repository placement room, monitored continuously and decommissioned for examination at various times. If containers have used fuel, and if they are installed with close-by monitoring, there may be an expectation that they would be retrieved and re-placed without the monitoring hardware as part of the final repository closure.

The third category of monitoring covers specialty tests that may occur across the repository and check aspects of performance of the as-placed containers. Important factors in planning for this monitoring are the longevity of the sensors and whether they could affect the system that they are monitoring. 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 controlled conditions in the engineered barriers.

12.1.4 Post-closure Monitoring

After closure the site is essentially fully returned to its intended end-state. The level of monitoring will be reduced but is expected to include continued environmental monitoring of surface and shallow groundwaters. Other monitoring that could be undertaken would focus on parameters that are indicative of the conditions near or within the repository. 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 microseismic arrays from surface or near-surface, and satellite monitoring of surface temperature and elevation change.

These will monitor the evolution of the site from the repository operations state to the post-closure state. Once future generations are comfortable that the repository is performing as designed, post-closure monitoring is expected to cease.

12.1.5 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. This is a topic of global interest, and Canada participates in these discussions (Pescatore et al. 2019).

The NWMO anticipates this would be done in different forms. It is anticipated that some type of marker would be provided at the site itself. There would also be land use controls imposed. And key information files would be preserved widely and in various formats. For example, a set of essential records defined per international guidance could be prepared, and distributed at municipal, provincial, national and probably international levels for archiving.

13. REGULATORY FRAMEWORK

Canada has a well-developed regulatory framework for evaluation of safety of nuclear facilities and for transportation of nuclear materials. This framework is consistent with international practice (e.g., IAEA 2011a, 2011b. 2018).

The NWMO facility is defined as a Class IB nuclear facility under the federal *Nuclear Safety and Control Act* and regulations. Relevant regulations include General Nuclear Safety and Control Regulations (SOR/2000-202), Radiation Protection Regulations (SOR/2000-203) and Nuclear Security Regulations (SOR/2000-209).

Transportation of used nuclear fuel is regulated by the CNSC and Transport Canada. Relevant regulations include Packaging and Transport of Nuclear Substances Regulations (SOR/2015-145) and Transportation of Dangerous Goods Regulations (SOR/2001-286).

The first formal step in approving the facility will be an assessment in accordance with the federal *Impact Assessment Act*. Subsequently licences are required from the Canadian regulator, the Canadian Nuclear Safety Commission (CNSC), to prepare the site, to construct the repository, to operate the facility, to decommission the facility, and eventually to abandon the site (release it from regulatory licence).

In evaluating any proposed repository, CNSC would consider the extent to which the proposal addresses the principles set out in their regulatory document REGDOC-2.11 (CNSC 2021a):

a) generation of radioactive waste is minimized to the extent practicable by the implementation of design measures, operating procedures and decommissioning practices;

b) the management of radioactive waste is commensurate with its radiological, chemical and biological hazard to the health and safety of persons and the environment and to national security;

c) the assessment of future impacts of radioactive waste on the health and safety of persons and the environment encompasses the period of time when the maximum impact is predicted to occur;

d) predicted impacts on the health and safety of persons and the environment from the management of radioactive waste are no greater than the impacts that are permissible in Canada at the time of the regulatory decision;

e) measures needed to prevent unreasonable risk to present and to future generations from the hazards of radioactive waste are developed, funded and implemented as soon as reasonably practicable; and

f) trans-border effects on the health and safety of persons and the environment that could result from the management of radioactive waste in Canada are not greater than the effects experienced in Canada.

14. UNCERTAINTIES AND FUTURE WORK

A variety of studies are ongoing in site characterization, environmental baseline, engineering and safety assessment, which will improve our understanding of the site and its safety basis.

The most important site uncertainty for safety purposes is understanding the geometry and properties of fractures in the subsurface within the site. This includes lineaments defined at ground surface and interpreted to extend into the subsurface as fracture zones, and subhorizontal structures encountered in boreholes and identified in seismic data. Presently, the underground locations of the larger fractures have been estimated based on surface observations and known understanding of how these fractures form. Direct measurements in the six boreholes to date, and preliminary interpretations of the 2D seismic studies are consistent with this understanding. There remains some uncertainty regarding whether or not any fracture zones at the Revell Site were re-activated as post-glacial faults. While it is recognized that the Revell Site is located in a region of low seismic hazard, an investigation of potential recent (neotectonic) fault activity will be conducted as part of detailed site characterization, if the Revell Site is selected as the preferred site. Ongoing microseismic monitoring will also help identify any active faults in the region..

Another uncertainty is the hydraulic character of fractures and fracture zones. Fractures can be permeable pathways that would allow water to move through otherwise impermeable rock. However, many fractures were formed long ago, and have been altered and infilled by minerals, such that they are not simple permeable pathways. Fractures can also be a heterogeneous combination of both permeable and impermeable regions. Fracture distribution and intensity will therefore influence repository design. Understanding this aspect of the fractures depends on understanding the geological history of the Revell batholith (i.e., the timing and number of stages of fracture development), and implications on mineral infilling and alteration.

The locations and geometries of amphibolites, and other subordinate rock types, within the subsurface remain as an uncertainty. Although their position along the boreholes is relatively predictable, their size and distribution in volumes of rock away from the boreholes is less clear. The rock within and around these subordinate rock occurrences tends to be more fractured and in some cases these fractures are hydraulically conductive (i.e., permeable). These subsurface geological features will also influence repository design. Continued borehole drilling, seismic surveys, and modelling work will allow us to better assess the importance of these, and other, subordinate rock types at the site.

One challenge encountered during the drilling of deep boreholes was the lack of opportunity to collect groundwater samples. To date, the rock encountered has been “tight”, with only a few intervals having the ability to transmit sufficient groundwater for fluid geochemical analyses. The tightness of the rock is a favourable property in the context of containment and isolation functions of a repository. However, given this limited availability of groundwater samples, an emphasis is now placed on measuring the porewater chemistry in order to define hydrogeochemical trends with depth and the overall understanding of system evolution, including potential interactions with engineered barrier materials.

These uncertainties are being addressed through several approaches. Additional studies are planned, including more fieldwork and additional boreholes and rock property measurements, as part of the detailed site characterization program should the Revell Site be selected. Further information will also be obtained during repository construction by characterisation of shaft walls, tunnel walls, drilling of pilot holes, and other techniques to confirm the geology. The placement room positions, and the container placements within rooms, can be modified based on the direct observation of the rock during excavation and pilot hole drilling.

The wide range of measurements are being integrated into a conceptual model that will serve to improve the site understanding across all geoscientific disciplines. In addition, on-going activities such as seismic monitoring (Figure 14.1) and long-term pressure monitoring of boreholes are continually adding to a regional database of geoscientific information. Ultimately, the information on the current site characteristics will be documented in a Descriptive Geoscientific Site Model, and the past and projected future conditions (e.g., future ice ages) will be documented in a Geosynthesis report.

The next phase of site characterization will also help us better understand how to protect the surface and near surface environment during construction and operations. We will know more about site-specific biodiversity, meteorology and hydrology in particular, which will support site and design optimization.

A site-specific engineering design is presently being developed, as well as continued optimization of the engineered barriers, fuel handling and placement systems. In 2022, for example, full-scale non-nuclear trials at NWMO's test facility was conducted to demonstrate prototype placement equipment. The NWMO also is participating in several international projects, including observing the commissioning of the Olkiluoto repository in Finland.

For safety assessment, work is underway to develop site-specific models, including the interface between the underground geology and the surface environment. Important topics in the near term include incorporating the developing understanding of the fractures and of the groundwater chemistry into the safety assessment. Preliminary results indicate that the facility will be safe, even under major accidents. However as a nuclear and industrial facility, appropriate emergency services will need to be in place within the facility and in the region. Early assessment has identified some of these needs, and direction to address them (WSP 2022).

Figure 14.1: Photo of one of nine microseismic monitoring stations installed around the area in order to obtain more detailed information on site seismicity.

15. CONCLUSIONS

The Nuclear Waste Management Organization (NWMO) is presently in a multi-year process of identifying a safe site for a deep geological repository for Canada’s used nuclear fuel in an area with informed and willing hosts. This is similar to plans in other countries with nuclear power programs, particularly Finland and Sweden, which have approved sites for their deep geological repositories, and France and Switzerland which have identified their sites.

The fundamental safety objective of the project is to protect humans and the environment, including water, from harmful effects of radioactive or hazardous substances present in the used fuel.

The used fuel is initially very radioactive and hazardous. However, its radioactivity naturally decreases with time. The deep geological repository, including engineered and natural barriers, provides containment and isolation while this natural process occurs.

Previous discussions and studies have identified the Revell Site in northwestern Ontario and the South Bruce Site in southern Ontario as candidate repository sites.

This report focuses on the Revell Site. It summarizes the results to date with respect to why this site would be suitable from a technical perspective for hosting a repository. It is intended to support public discussion around site selection, and is focussed on those aspects that are likely of most interest to that discussion. This 2023 report incorporates new information available since the previous 2022 report was prepared. The new information includes more details in some topics, notably on the geology, design and safety assessment. These results, including site-specific favourable properties such as the presence of a hydrogeologically stable environment at depth, support the original conclusion.

Based on the assessment results to date, the NWMO is confident that a deep geological repository could be constructed at the Revell Site in a manner that would provide safe long-term containment and isolation for Canada’s used nuclear fuel.

This report is part of a larger and ongoing site assessment process. Ongoing and future technical work will include further site studies, design development and safety analyses to further check and clarify the safety basis. If the site is formally proposed for a repository, this work would ultimately be presented to Canadian federal regulators for an Impact Assessment and then for a series of licence applications. This is a process that will take years before approval to construct could be received. Even after construction and operations begin, there will be continued monitoring to ensure that the site is and remains suitable.

REFERENCES

Ackerley, N., V. Peci, J. Adams and S. Halchuk. 2021. Seismic activity in the Northern Ontario portion of the Canadian Shield: Annual progress report for the period January 01 – December 31, 2019. Nuclear Waste Management Organization Report NWMO-TR-2021-10. Toronto, Canada.

Åkesson, U. 2012. Laboratory Measurements of the Coefficient of Thermal Expansion of Olkiluoto Drill Core Samples. Posiva Oy Finland Report Posiva Working Report 2012-14. Finland.

Alba Geosolutions and Consulting. 2024. Future Mineral Resource Potential of the Revell Site. Nuclear Waste Management Organization Report NWMO-TR-2024-03. Toronto, Canada.

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

ANDRA. 2005. Dossier 2005 argile. Synthèse. Évaluation de la faisabilité du stockage géologique en formation argileuse. Agence nationale pour la gestion des déchets radioactif ANDRA Report. Paris, France.

ATLIS. 2018. Final Report, 1674 -Ignace Revell Batholith LiDAR survey. ATLIS Geomatics report. Calgary, Canada.

Bell, M. and E.P. Laine. 1985. Erosion of Laurentide region of North America by glacial and glaciofluvial processes. *Quaternary Research* 23, 154-174.

Berglund, S. and T. Lindborg. 2017. Monitoring Forsmark – evaluation and recommendations for programme update. Svensk Kärnbränslehantering Report SKB TR-15-01. Solna, Sweden.

Briggs, S (ed.) 2023. Technical program for long-term management of Canada's used nuclear fuel – Annual report 2022. Nuclear Waste Management Organization Report NWMO-TR-2023-01. Toronto, Canada.

Bruce Power. 2023. Environmental protection report 2022. Bruce Power. B-REP-07000-00015. Tiverton, Canada.

CEAA. 1998. Nuclear Fuel Waste Management and Disposal Concept: Report of the Nuclear Fuel Waste Management and Disposal Concept Environmental Assessment Panel. Canadian Environmental Assessment Agency. Ottawa, Canada.

Chandler, N. 2003. Twenty years of underground research at Canada's URL. Proceedings, Waste Management 2003 (WM2003). Tucson, United States.

CNL. 2021. Near Surface Disposal Facility, Deep River, Renfrew County, Ontario, Environmental Impact Statement, Volume 1: Executive Summary. Canadian Nuclear Laboratories, Report 232-509220-021-000. Chalk River, Canada.

CNSC. 2000. Nuclear Safety and Control Act: Radiation Protection Regulations. Government of Canada, Canada Gazette Part II, Vol. 134, No. 13, SOR/2000-203, 31 May 2000. Ottawa, Canada.

CNSC. 2017. Environmental Protection: Environmental principles, assessments and protective measures, version 1.1. Canadian Nuclear Safety Commission Regulatory Document REGDOC-2.9.1. Ottawa, Canada.

CNSC. 2021a. Framework for Radioactive Waste Management and Decommissioning in Canada. Canadian Nuclear Safety Commission Regulatory Document REGDOC-2.11, Version 2. Ottawa, Canada.

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

CNSC. 2022. Safety Analysis for Class 1B Nuclear Facilities. Canadian Nuclear Safety Commission Regulatory Document REGDOC-2.4.4. Ottawa, Canada.

CNSC. 2023a. "Radiation dose", updated March 2023. Canadian Nuclear Safety Commission, Ottawa, Canada. http://www.cnsc.gc.ca/eng/resources/radiation/introduction-to-radiation/radiation-doses.cfm

CNSC. 2023b. Independent Environmental Monitoring Program (IEMP). Canadian Nuclear Safety Commission website https://www.nuclearsafety.gc.ca/eng/resources/maps-of-nuclear-facilities/iemp/index.cfm

Cooperail. 2015. Operation Smash Hit 1984 CEGB Original [Video]. Youtube. Available at https://www.youtube.com/watch?v=hTshPr2TogE

Cramer, J. and J. Smellie. 1994. Final report for the AECL/SKB Cigar Lake analog study. Atomic Energy of Canada Limited Report AECL-10851, COG-93-00147, SKB-TR-94-00004. Pinawa, Canada.

CSA. 2015. Environmental monitoring programs at Class I nuclear facilities and uranium mines and mills. Canadian Standards Association CSA N288.4-10 (R2015). Toronto, Canada.

Davis, W.D. 2023. Phase 2 Initial Borehole Drilling and Testing, Ignace Area, U-Pb Geochronology by LA-ICPMS for Borehole IG_BH01. Nuclear Waste Management Organization report APM-REP-01332-0421. Toronto, Canada.

DesRoches, A., Sykes, M., Parmenter, A. and E. Sykes. 2018. Lineament Interpretation of the Revell Batholith and surrounding Greenstone Belts. Nuclear Waste Management Organization Report NWMO-TR-2018-19. Toronto, Canada.

Drury, M. and T. Lewis. 1983. Water movement within lac du bonnet batholith as revealed by detailed thermal studies of three closely-spaced boreholes. *Tectonophysics*, 95(3-4), 337-351.

Easton, E. 2014. Why the nine metre drop test bounds the impacts from most severe accidents. Nuclear Waste Management Organization Report NWMO-TR-2014-04. Toronto, Canada.

Frape, S.K., and P. Fritz. 1987. Geochemical trends for groundwaters from the Canadian Shield; in *Saline water and gases in crystalline rocks*, Editors: Fritz, P., and Frape, S.K.; Geological Association of Canada Special Paper 33, 19-38.

Golder. 2011. Initial screening for siting a deep geological repository for Canada's used nuclear fuel. The Corporation of the Township of Ignace, Ontario. Golder Associates Report 10-1152-0110 (2000); NWMO APM-REP-06143-32404. Mississauga, Canada.

Golder. 2013. Phase I desktop geoscientific preliminary assessment of potential suitability for siting a deep geological repository for Canada's used nuclear fuel. Township of Ignace, Ontario. Golder Associates Report 12-1152-0026 (3000); NWMO Report APM-REP-06144-0011. Mississauga, Ontario.

Golder. 2017. Phase 2 geoscientific preliminary assessment. Initial findings, Township of Ignace and area, Ontario. Golder Associates Report 1532407 (7000); NWMO Report APM-REP-01332-0227. Mississauga, Canada.

Golder. 2020. Climate change impacts on climate variables for a deep geological repository (Ignace study area). Nuclear Waste Management Organization Report NWMO-TR-2020-04. Toronto, Canada.

Golder (Golder Associates Ltd.) and PGW (Paterson, Grant and Watson Ltd.). 2017. Detailed Geological Mapping – Ignace Ontario – APM Phase 2 Assessment. Prepared for Nuclear Waste Management Organization report APM-REP-01332-0225. Toronto, Canada.

Golder Associates Ltd., 2022a. Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP4b Data Report – Geomechanical Testing of Core for IG_BH03. Nuclear Waste Management Organization report APM-REP-01332-0252. Toronto, Canada.

Golder Associates Ltd., 2022b. Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP10 – Rock Mass Classification for IG_BH02. Nuclear Waste Management Organization report APM-REP-01332-0304. Toronto, Canada.

Grasty, R.L. and J.R. LaMarre. 2004. The annual effective dose from natural sources of ionising radiation in Canada. *Radiation Protection Dosimetry* 108, 215-226.

Guo, R. 2023. Calculation of thermal-hydraulic-mechanical response of a deep geological repository for radioactive used fuel in granite. *Inter J Rock Mechanics and Mining Science* 170 #105435. doi.org/10.1016/j.ijrmms.2023.105435

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

Hall A. M, K. Ebert, B. W. Goodfellow, C. Hättestrand, J. Heyman, M. Krabbendam, S. Moon, A. P. Stroeven. 2019. Past and future impact of glacial erosion in Forsmark and Uppland. Final report. Svensk Kärnbränslehantering Report SKB TR-19-07. Solna, Sweden.

IAEA. 2011a. Disposal of Radioactive Waste. International Atomic Energy Agency Specific Safety Requirements SSR-5. Vienna, Austria.

IAEA. 2011b. Geological Disposal Facilities for Radioactive Waste. International Atomic Energy Agency Specific Safety Guide No. SSG-14. Vienna, Austria.

IAEA. 2014. Monitoring and surveillance of radioactive waste disposal facilities. International Atomic Energy Agency Specific Safety Guide No. SSG-31. Vienna, Austria.

IAEA. 2018. Regulations for the Safe Transport of Radioactive Material. International Atomic Energy Agency Specific Safety Requirements SSR-6, Rev 1. Vienna, Austria.

Keech, P., M. Behazin, J. Binns and S. Briggs. 2020. An update on the copper corrosion program for the long-term management of used nuclear fuel in Canada. *Materials and Corrosion* 72, 25-31. doi:10.1002/maco.202011763

Lee, A. and R. Heystee. 2014. Used fuel deep geological repository shaft versus ramp trade-off study. Nuclear Waste Management Organization Report NWMO TR-2014-22. Toronto, Canada.

Leupin, O., M Birgersson, O. Karnland, P. Korkeakoski, P. Sellin, U. Mader and P. Wersin. 2015. Montmorillonite stability under near-field conditions. Nagra Technical Report NTB 14-12. Switzerland.

Liberda, K. 2020. Preliminary radon assessment for a used fuel deep geological repository. Nuclear Waste Management Organization Report NWMO-TR-2019-09. Toronto, Canada.

MOE (Ministry of the Environment). 2003. Stormwater management planning and design manual. Ontario Ministry of the Environment, Conservation, and Parks (formerly MOE at publication). Ontario, Canada.

Nagra. 2002. Project Opalinus Clay: Safety Report. Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (Entsorgungsnachweis). Nagra Technical Report NTB-02-05. Wettingen, Switzerland.

Nanometrics. 2023. Revell Site Microseismic Monitoring Project Annual Event Summary Report (January 1, 2022 - December 31, 2022). Nuclear Waste Management Organization Report APM-REP-01332-0422. Toronto, Canada.

Naylor, S., A. Wickert, D. Edmonds and B. Yanites. 2021. Landscape Evolution Under the Laurentide Icesheet. *Science Advances* 7, 48.

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

NWMO. 2013. Phase 1 Desktop Assessment, Environment Report. Township of Ignace, Ontario. Nuclear Waste Management Organization Report APM-REP-06144-0010. Toronto, Canada.

NWMO. 2017. Postclosure safety assessment of a used fuel repository in crystalline rock. Nuclear Waste Management Organization Report NWMO-TR-2017-02. Toronto, Canada.

NWMO. 2020. Preliminary radon assessment for a used fuel deep geological repository. Nuclear Waste Management Organization Report NWMO-TR-2019-09. Toronto, Canada.

NWMO. 2021a. Deep Geological Repository conceptual design report crystalline / sedimentary rock. Nuclear Waste Management Organization Report APM-REP-00440-0211. Toronto, Canada.

NWMO. 2021b. Deep Geological Repository transportation system conceptual design report crystalline / sedimentary rock. Nuclear Waste Management Organization Report APM-REP-00440-0209-R001. Toronto, Canada.

NWMO. 2021c. Preliminary Transportation Plan. Nuclear Waste Management Organization. Toronto, Canada.

NWMO. 2022. Nuclear fuel waste projections in Canada – 2022 Update. Nuclear Waste Management Organization Report NWMO-TR-2022-17. Toronto, Canada.

OECD (Organisation for Economic Co-operation and Development). 2020. Management and Disposal of High-Level Radioactive Waste: Global Progress and Solutions. Paris, France.

Park, Y-J., E.A. Sudicky and J.F. Sykes. 2009. Effects of shield brine on the safe disposal of waste in deep geologic environments. *Advances in Water Resources* 32, 1352–1358.

Parmenter, A., L. Waffle and A. DesRoches. 2020. Bedrock geology of the Revell Batholith and surrounding greenstone belts. Nuclear Waste Management Organization Report NWMO-TR-2020-08. Toronto, Canada.

Parmenter, A., L. Waffle and A. DesRoches. 2022a. Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP10 – Geological Integration Report for Borehole IG_BH03. Nuclear Waste Management Organization report APM-REP-01332-0266. Toronto, Canada.

Parmenter, A., L. Waffle and A. DesRoches. 2022b. Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP10 – Geological Integration Report for Borehole IG_BH02. Nuclear Waste Management Organization report APM-REP-01332-0265. Toronto, Canada.

Parmenter, A., L. Waffle, A. DesRoches, J. Carvalho and A. Neufeld. 2022c. Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP10 – Geological Integration Report for Borehole IG_BH01. Nuclear Waste Management Organization report APM-REP-01332-0260. Toronto, Canada.

Peltier, W.R. 2011. Long-Term Climate Change. Nuclear Waste Management Organization Report NWMO DGR-TR-2011-14. Toronto, Canada.

Percival, J.A. and R.M. Easton. 2007. Geology of the Canadian Shield in Ontario: An Update. Ontario Geological Survey Report Open File Report 6196. Ontario, Canada.

Pescatore C, S Hotzel, A Berckmans, A Claudel, J-N Dumont, S Tunbrant, S Wisbey, A Van Luik and J Schroeder. 2019. Preservation of Records, Knowledge and Memory across generations. Final Report of the RK and M Initiative. OECD/NEA No. 7421, Organization for Economic Cooperation and Development / Nuclear Energy Agency, Paris, France.

Posiva. 2007. Safety assessment for a KBS-3H spent nuclear fuel repository at Olkiluoto, Summary report. Posiva Report 2007-06. Olkiluoto, Finland.

Posiva. 2012. Monitoring at Olkiluoto – A programme for the period before repository operation. Posiva Report 2012-01. Olkiluoto, Finland.

RWM. 2016. Geological Disposal, Generic Environmental Safety Case – Main Report. UK Nuclear Decommissioning Authority (Radioactive Waste Management) NDA Report DSSC/203/01. Didcot, United Kingdom.

RI. 2022. "Radiation Dose", reviewed November 2022, RadiologyInfo.Org, sponsored by Radiological Society of North America and American College of Radiology. https://www.radiologyinfo.org/en/info/safety-xray

Robin, C.M.I., M. Craymer, R. Ferland, T.S. James, E. Lapelle, M. Piraszewski and Y. Zhao. 2020. NAD83v70VG: A new national crustal velocity model for Canada. Geomatics Canada Open File 0062.

Rodriguez, A. and R. Brown. 2021. A preliminary flood hazard assessment at the Ignace study area. Nuclear Waste Management Organization Report NWMO-TR-2021-26. Toronto, Canada.

SGL (Sander Geophysics Ltd.). 2015. Phase 2 Geoscientific Preliminary Assessment, Acquisition, Processing and Interpretation of High-Resolution Airborne Geophysical Data, Township of Ignace, Ontario. Nuclear Waste Management Organization Report APM-REP-06145-0002. Toronto, Canada.

SGL (Sander Geophysics Limited). 2020. 3D Geophysical Forward and Inversion Modelling of the Revell Batholith and Surrounding Greenstone Belt. Nuclear Waste Management Organization Report, APM-REP-01332-0270. Toronto, Canada.

Sella, G., S. Stein, T. Dixon, M. Craymer, T. James, S. Mazzotti and R. Dokka. 2007. Observation of glacial isostatic adjustment in "stable" North America with GPS, *Geophysical Research Letters* 34, L02306. doi 10.1029/2006GL027081

SKB. 2000. A natural analogue for copper waste canisters: the copper-uranium mineralised concretions in the Permian mudrocks of south Devon, United Kingdom. Svensk Kärnbränslehantering Report SKB TR-00-11. Stockholm, Sweden.

SKB. 2007. Thermal Properties – Site descriptive modelling Forsmark – stage 2.2. Svensk Kärnbränslehantering Report SKB R-07-47. Stockholm, Sweden.

SKB. 2008. Site description of Forsmark at completion of the site investigation phase, SDM-Site Forsmark. Svensk Kärnbränslehantering Report SKB TR-08-05. Stockholm, Sweden.

SKB. 2011. Long-term safety for the final repository for spent nuclear fuel at Forsmark.Main report of the SR-Site project. Svensk Kärnbränslehantering Report SKB TR-11-01. Stockholm, Sweden.

Snowdon, A., S. Normani and J. Sykes. 2021. Analysis of crystalline rock permeability versus depth in a Canadian Precambrian rock setting. *Journal of Geophysical Research: Solid Earth* 126(5). doi.org/10.1029/2020JB020998

SRK (SRK Consulting Inc.) and Golder (Golder Associates Ltd.), 2015. Phase 2 Geoscientific Preliminary Assessment, Observation of General Geological Features, Township of Ignace, Ontario. Nuclear Waste Management Organization Report APM-REP-06145-0004. Toronto, Canada.

Stone, D., D. Kamineni, A. Brown and R. Everit. 1989. A comparison of fracture styles in two granite bodies of the Superior Province. *Canadian Journal of Earth Sciences* 26(2), 387-403.

Storey, C.C. 1986. Building and ornamental stone inventory in the Districts of Kenora and Rainy River. Ontario Geological Survey, Mineral Deposits Circular 27. Ontario, Canada.

Stuhne, G. and W.R. Peltier. 2015. Surface boundary conditions during long-term climate change. Nuclear Waste Management Organization Report NWMO-TR-2015-16. Toronto, Canada.

Stuhne, G. and W.R. Peltier. 2016. Sensitivity Analyses of Surface Boundary Conditions During Long-Term Climate Change. Nuclear Waste Management Organization Report NWMO-TR-2016-19. Toronto, Canada.

Stuhne, G. and W.R. Peltier. 2023. Sensitivity Analyses of Surface Boundary Conditions During Long-Term Climate Change. Nuclear Waste Management Organization Report NWMO-TR-2023-10. Toronto, Canada.

US DOE. 2016. A Historical Review of the Safe Transport of Nuclear Fuel. Report prepared for United States Department of Energy. FCRD-NFST-2016-000474, Rev 1; ORNL/SR-2016/261 Rev 1. United States.

Vibrometric. 2022. 2D Seismic Investigations, Ignace Area, Report. Nuclear Waste Management Organization Report APM-REP-01332-0308. Toronto, Canada.

Yong, S. and S. Maloney. 2015. An update to the Canadian Shield stress database. Nuclear Waste Management Organization Report NWMO-TR-2015-18. Toronto, Canada.

Wikjord, A., P. Baumgartner, L. Hjohnson, F. Stanchell, R. Zach and B. Goodwin. 1996. The disposal of Canada's nuclear fuel waste: A study of postclosure safety of in-room emplacement of used CANDU fuel in copper containers in permeable plutonic rock, Volume I: Summary. Atomic Energy of Canada Limited report AECL-11494-1, COG-95-552-1. Pinawa, Canada.

WSP-Golder Associates Ltd. 2022. Phase 2 Initial Borehole Drilling and Testing at IG_BH04/05/06, Ignace Area. WP12 Data Report – Vertical Seismic Profiling for IG_BH04. Nuclear Waste Management Organization report APM-REP-01332-0284. Toronto, Canada.

WSP Canada Inc. 2022. Ignace area infrastructure: Transportation and emergency response study. Report prepared for the Township of Ignace. Canada.

WSP Canada Inc. 2023a. Phase 2 Initial Borehole Drilling and Testing at IG_BH04/05/06, Ignace Area. WP12 Data Report – Vertical Seismic Profiling for IG_BH05. Nuclear Waste Management Organization report APM-REP-01332-0368. Toronto, Canada.

WSP Canada Inc. 2023b. Phase 2 Initial Borehole Drilling and Testing at IG_BH04/05/06, Ignace Area. WP12 Data Report – Vertical Seismic Profiling for IG_BH06. Nuclear Waste Management Organization report APM-REP-01332-0369. Toronto, Canada.

APPENDIX A: List of Published Site-Specific Technical Reports

Report #	Report Title
APM-REP-01332-0225	Phase 2 Geoscientific Preliminary Assessment, Geological Mapping, Township of Ignace and area, Ontario
APM-REP-01332-0227	Phase 2 Geoscientific Preliminary Assessment, Initial Findings, Township of Ignace and Area, Ontario
APM-REP-01332-0228	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP1 Data Report - Completion of Demobilization and Decommissioning Activities at IG_BH01 Test Site, Ignace, ON
APM-REP-01332-0229	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP2 Data Report - Borehole Drilling and Coring for IG_BH01
APM-REP-01332-0230	WP03 Data Report - Geological and Geotechnical Core Logging, Photography and Sampling for IG_BH01
APM-REP-01332-0231	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP4a Data Report - Petrophysical Testing of Core for IG_BH01
APM-REP-01332-0232	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP4b Data Report - Geomechanical Testing of Core for IG_BH01
APM-REP-01332-0233	Phase 2 Initial Borehole Drilling and Testing, Ignace Area: WP04C Data Report – Porewater Extraction and Analysis and Petrographic Analysis for IG_BH01
APM-REP-01332-0234	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP5 Data Report - Geophysical Well Logging for IG_BH01
APM-REP-01332-0235	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP6 Data Report - Hydraulic Testing for IG_BH01.
APM-REP-01332-0236	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP7 Data Report - Opportunistic Groundwater Sampling for IG_BH01
APM-REP-01332-0237	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP9 Data Report - Westbay MP38 Casing Completion for IG_BH01
APM-REP-01332-0239	Final Report on 2017 Ignace Revell Batholith LiDAR Survey
APM-REP-01332-0240	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP02 Data Report - Borehole Drilling and Coring for IG_BH02
APM-REP-01332-0241	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP02 Data Report - Borehole Drilling and Coring for IG_BH03
APM-REP-01332-0242	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP02 Data Report – Borehole Drilling and Coring for IG_BH04.
APM-REP-01332-0243	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP02 Data Report – Borehole Drilling and Coring for IG_BH05.
APM-REP-01332-0244	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP02 Data Report – Borehole Drilling and Coring for IG_BH06.
APM-REP-01332-0245	Phase 2 Initial Borehole Drilling and Testing, Ignace Area: WP04C Data Report – Porewater Extraction and Analysis and Petrographic Analysis for IG_BH02
APM-REP-01332-0246	Phase 2 Initial Borehole Drilling and Testing, Ignace Area: WP04C Data Report – Porewater Extraction and Analysis and Petrographic Analysis for IG_BH03
APM-REP-01332-0247	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. 2019 Pressure Monitoring of Westbay MP38 System at IG_BH01
APM-REP-01332-0249	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP03 Data Report - Geological and Geotechnical Core Logging, Photography and Sampling for IG_BH02

APM-REP-01332-0250	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP03 Data Report - Geological and Geotechnical Core Logging, Photography and Sampling for IG_BH03
APM-REP-01332-0251	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP04b Data Report - Geomechanical Testing of Core for IG_BH02.
APM-REP-01332-0252	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP04b Data Report - Geomechanical Testing of Core for IG_BH03.
APM-REP-01332-0253	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP07 Data Report – Opportunistic Groundwater Sampling for IG_BH03.
APM-REP-01332-0254	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP07 Data Report – Opportunistic Groundwater Sampling for IG_BH02.
APM-REP-01332-0255	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP06 Data Report – Hydraulic Testing for IG_BH03.
APM-REP-01332-0256	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP06 Data Report – Hydraulic Testing for IG_BH02.
APM-REP-01332-0257	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP08 Data Report. Temporary Well Sealing for IG_BH02.
APM-REP-01332-0258	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP03 Data Report – Geological and Geotechnical Core Logging, Photography and Sampling for IG_BH05.
APM-REP-01332-0259	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP09 Data Report – Westbay MP38 Casing Completion for IG_BH03
APM-REP-01332-0260	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP10 - Geological Integration Report for Borehole IG_BH01
APM-REP-01332-0261	Phase 2 Initial Borehole Drilling, Ignace Area. WP01 Commissioning Report – Site Infrastructure Setup for IG_BH03
APM-REP-01332-0262	Phase 2 Initial Borehole Drilling and Testing, Ignace Area - WP01 Site Demobilization Report - Site Infrastructure for IG_BH03
APM-REP-01332-0263	Phase 2 Initial Borehole Drilling, Ignace Area. WP01 Commissioning Report – Site Infrastructure Setup for IG_BH02
APM-REP-01332-0264	Phase 2 Initial Borehole Drilling and Testing, Ignace Area - WP01 Site Demobilization Report - Site Infrastructure for IG_BH02
APM-REP-01332-0265	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP10 – Geological Integration Report for Borehole IG_BH02
APM-REP-01332-0266	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP10 - Geological Integration Report for Borehole IG_BH03
APM-REP-01332-0268	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP05 Data Report - Geophysical Well Logging for IG_BH03.
APM-REP-01332-0269	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP05 Data Report - Geophysical Well Logging for IG_BH02
APM-REP-01332-0270	3D Geophysical Forward and Inversion Modelling of the Revell Batholith and Surrounding Greenstone Belts
APM-REP-01332-0278	Phase 2 Initial Borehole Drilling and Testing at IG_BH04/05/06 - Ignace Area. WP02 Data Report - Borehole Drilling and Flushing for IG_BH04
APM-REP-01332-0280	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP06 Data Report – Hydraulic Testing for IG_BH04.

APM-REP-01332-0281	Phase 2 Initial Borehole Drilling and Testing at IG_BH04/05/06, Ignace Area. WP07 Data Report - Opportunistic Groundwater Sampling for IG_BH04.
APM-REP-01332-0282	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP08 Data Report – Temporary Well Sealing for IG_BH04.
APM-REP-01332-0284	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP12 Data Report – Vertical Seismic Profiling for IG_BH04.
APM-REP-01332-0289	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP05 Data Report - Geophysical Well Logging and Interpretation for Upper 100 m of IG_BH04
APM-REP-01332-0293	Phase 2 Initial Borehole Drilling and Testing at IG_BH04/05/06, Ignace Area. WP01 Commissioning Report – Site Infrastructure Setup for IG_BH04
APM-REP-01332-0294	Phase 2 Initial Borehole Drilling and Testing at IG_BH04/05/06 - Ignace Area. WP01 Commissioning Report – Site Infrastructure Setup for IG_BH05
APM-REP-01332-0296	Westbay Fluid Pressure Monitoring and Groundwater Sampling in Ignace Boreholes for IGBH01 and IGBH03.
APM-REP-01332-0302	Phase 2 Initial Borehole Drilling and Testing at IG_BH04/05/06 - Ignace Area. WP01 Commissioning Report – Site Infrastructure Setup for IG_BH06
APM-REP-01332-0303	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP10 - Rock Mass Classification for IG_BH01
APM-REP-01332-0304	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP10 - Rock Mass Classification for IG_BH02
APM-REP-01332-0305	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP10 - Rock Mass Classification for IG_BH03
APM-REP-01332-0306	Phase 2 Initial Borehole Drilling and Testing at IG_BH04/05/06, Ignace Area. WP01 Site Demobilization Report - Site Infrastructure for IG_BH04
APM-REP-01332-0308	Phase 2 – 2D Seismic Investigation - Ignace Area, Report
APM-REP-01332-0312	Phase 2 Initial Borehole Drilling and Testing at IG_BH04/05/06, Ignace Area. WP01 Site Demobilization Report - Site Infrastructure for IG_BH05
APM-REP-01332-0340	Ignace Area Seismic Monitoring Project Annual Event Summary Report, November 2020 - December 2021
APM-REP-01332-0341	Phase 2 Initial Borehole Drilling, Ignace Area. Site Commissioning Technical Report - IG_BH04
APM-REP-01332-0347	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP04C Data Report – Porewater Extraction and Analysis and Petrographic Analysis for IG_BH04.
APM-REP-01332-0353	Phase 2 Initial Borehole Drilling and Testing at IG_BH04/05/06, Ignace Area. WP01 Site Demobilization Report - Site Infrastructure for IG_BH06
APM-REP-01332-0355	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP04F Data Report – Measurement of Surface Area and Cation Exchange Capacity of Core for IG_BH04.
APM-REP-01332-0356	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP05 Data Report – Geophysical Well Logging and Interpretation for IG_BH04.
APM-REP-01332-0357	Phase 2 Initial Borehole Drilling and Testing at IG_BH04/05/06, Ignace Area. WP07 Data Report - Opportunistic Groundwater Sampling for IG_BH05.

APM-REP-01332-0358	Phase 2 Initial Borehole Drilling and Testing at IG_BH04/05/06, Ignace Area. WP07 Data Report - Opportunistic Groundwater Sampling for IG_BH06.
APM-REP-01332-0364	Phase 2 Initial Borehole Drilling and Testing at IG_BH04/05/06 - Ignace Area. WP09 Data Report - Westbay Monitoring System Installation for IG_BH05.
APM-REP-01332-0365	Phase 2 Initial Borehole Drilling and Testing at IG_BH04/05/06 - Ignace Area. WP09 Data Report - Westbay Monitoring System Installation for IG_BH06.
APM-REP-01332-0366	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP05 Data Report – Geophysical Well Logging and Interpretation for IG_BH05.
APM-REP-01332-0367	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP05 Data Report – Geophysical Well Logging and Interpretation for IG_BH06.
APM-REP-01332-0368	Phase 2 Initial Borehole Drilling and Testing at IG_BH04/05/06 - Ignace Area. WP12 Data Report – Vertical Seismic Profiling for IG BH05.
APM-REP-01332-0369	Phase 2 Initial Borehole Drilling and Testing at IG_BH04/05/06 - Ignace Area. WP12 Data Report – Vertical Seismic Profiling for IG BH06.
APM-REP-01332-0372	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP10 Data Report – Single Borehole Data Integration for IG_BH04.
APM-REP-01332-0375	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. Thin Section Petrography and Lithogeochemical Analysis of Core Samples from IG_BH01.
APM-REP-01332-0376	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. Thin Section Petrography and Lithogeochemical Analysis of Core Samples from IG_BH02 and IG_BH03.
APM-REP-01332-0377	Density, Porosity, Water Content, and Hydraulic Conductivity Testing on Core Samples from Ignace Boreholes 01-03.
APM-REP-01332-0382	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP03 Data Report – Geological and Geotechnical Core Logging, Photography and Sampling for IG_BH05.
APM-REP-01332-0383	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP03 Data Report – Geological and Geotechnical Core Logging, Photography and Sampling for IG_BH06.
APM-REP-01332-0385	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP1 Site Infrastructure Commissioning at IG_BH01.
APM-REP-01332-0395	Phase 2 Initial Borehole Drilling and Testing at IG_BH04/05/06 - Ignace Area. WP06 Data Report Hydraulic Testing for IG_BH05.
APM-REP-01332-0396	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. WP06 Data Report – Hydraulic Testing for IG_BH06.
APM-REP-01332-0464	Phase 2 Initial Borehole Drilling and Testing, Ignace Area. Thin Section Petrography and Lithogeochemical Analysis of Core Samples from IG_BH01 through IG_BH04.
APM-REP-06145-0001	Phase 2 Geoscientific Preliminary Assessment, Findings from Initial Field Studies

APM-REP-06145-0002	Phase 2 Geoscientific Preliminary Assessment, Acquisition, Processing and Interpretation of High-Resolution Airborne Geophysical Data
APM-REP-06145-0003	Phase 2 Geoscientific Preliminary Assessment, Lineament Interpretation
APM-REP-06145-0004	Phase 2 Geoscientific Preliminary Assessment, Observation of General Geological Features
APM-REP-07000-0206	Phase 2: Preliminary Environmental Studies
NWMO-TR-2018-19	Lineament Interpretation of the Revell Batholith and Surrounding Greenstone Belts
NWMO-TR-2020-07	3D Seismic Wave Velocity Model for the Revell Batholith and Surrounding Region
NWMO-TR-2020-08	Bedrock Geology of the Revell Batholith and Surrounding Greenstone Belts
NWMO-TR-2021-10	Seismic Activity in the Northern Ontario Portion of the Canadian Shield: Annual Progress Report for the Period January 01 – December 31, 2019.
NWMO-TR-2021-12	3D Site-Scale Geological Model in the Revell Batholith: Model Version 1.0
NWMO-TR-2022-23	Seismic Activity in the Northern Ontario Portion of the Canadian Shield: Annual Progress Report for the Period January 01, 2020 – December 31, 2021.
NWMO-TR-2022-24	Sorption Testing for Se, Tc, Np, U and Eu for IG_BH01, IG_BH03 and IG_BH05.
NWMO-TR-2023-10	Sensitivity Analyses of Surface Boundary Conditions During Long-Term Climate Change
NWMO-TR-2024-03	Future Mineral Resource Potential of the Revell Site.