Confidence in Safety – Revell Site

NWMO-TR-2022-14 March 2022

Nuclear Waste Management Organization

NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

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

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

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Verified by:	S Hirschorn		
Approved by:	C Boyle		

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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 similar to plans in other countries with nuclear power programs, including in particular Finland and Sweden which have approved sites for their planned deep geological repositories.

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; in particular 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 Metis communities in both siting areas are working with the NWMO as part of the site selection process. Neither of the two sites have yet been identified as the preferred site.

This report focuses on the Revell Site. It summarizes the results as of early 2022 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 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 confirm and extend the results to date. These would ultimately be presented to Canadian federal regulators for an Impact Assessment and a series of licence applications. This is a process that will take years before a final approval to construct could be received. During construction and operations, there will be continued monitoring to ensure that the site is, and remains, suitable for long-term containment and isolation of used nuclear fuel.

The NWMO's assessment of the suitability of the Revell Site is based on both intrinsic characteristics of the repository approach, as well as Revell Site specific results acquired to date. These are described in more detail within this report, but key points are as follows:

1. The favourable characteristics of the geological setting.

- The Revell Site is within the Revell batholith. This rock unit formed about 2.7 billion years ago, and is approximately 40 km long, 15 km wide, and estimated to be about 3 km deep at the site. This rock unit has the depth, breadth and volume to isolate the repository from surface disturbances and changes caused by human activities and natural events.

- The rocks of the Revell batholith 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. These rocks are capable of removing the decay heat from the fuel and withstanding the natural stresses and thermal stresses induced by a repository.

- The composition of the groundwater samples and the porewater from core samples shows trends with depth that are consistent with expectations for the Canadian Shield. Based on the results to-date, oxidizing conditions are not expected at potential repository depth. This is favorable for the durability of the used fuel container.

- 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. Also, for all groundwater samples collected during drilling to-date, the total dissolved sulphide concentrations were very low. These are favorable for the durability of the used fuel container.

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

2. The stability of the geological setting.

- The Revell batholith is about 2.7 billion years old.

- The Revell Site is located in a stable, seismically quiet setting in the Canadian Shield at the heart of the North American continent, far from tectonic plate boundaries. This is favorable for long-term stability.

- There is currently 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.

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 within the Revell batholith at this site from past explorations or site data collected to date. This reduces the risk of inadvertent future human intrusion into the repository.

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. This degree of homogeneity is favourable for predicting the overall host rock structure and characteristics from the available and planned studies.

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 containers and bentonite-clay based seals.

- The used fuels are primarily a durable uranium-oxide solid ceramic material.

- 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.

- 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.

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

- 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. This degree of homogeneity is favourable for construction of a repository.

- The rock mass properties in the Revell Site are typical of high quality, strong, crystalline rocks.

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

- The Revell Site has suitable underground area for emplacement of all Canada's projected used fuel.

- A preliminary conceptual design has been developed for the repository facilities and is consistent with international best practice. 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. There is high confidence that the surface area and infrastructure can support the construction, operations, and closure of the repository.

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 transport 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 safety 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 licencing a repository. It is consistent with international guidance.

- Safety assessment studies to date for other crystalline rock sites have indicated that a repository in these rocks can perform well, with no impacts on human health. An assessment specific to the Revell Site is currently under development, but preliminary indications are consistent with these other studies.

- Baseline monitoring is in-place or underway, including borehole, shallow groundwater, surface water, biodiversity, seismic and meteorological monitoring.
  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, including water.

Overall, 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 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 bedrock to safely contain and isolate used nuclear fuel, and more about developing and documenting a thorough quantitative understanding of the site. The uncertainty in geometry and property of fractures in the subsurface within the site in particular will require additional effort in the future; it will be addressed through both future detailed site characterization as well as through optimization of repository emplacement rooms during the underground excavation. The design of the surface and underground facilities will continue throughout site characterization.

The safety of the proposed site would be confirmed through a rigorous regulatory review of the facility design and safety case. The decision-making process and implementation would extend over decades. The associated 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, would have the ability to adjust to new information and technologies to improve understanding and optimize performance.

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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 2021). This is similar to plans in other countries with nuclear power programs, including in particular Finland and Sweden which have approved sites.

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 the Revell Site in northwestern Ontario and the South Bruce Site in southern Ontario as candidate repository sites. Neither of the two sites have yet been identified as the preferred site, as there are technical studies and community partnership discussions underway, and decisions to be made by both the NWMO and communities.

This report focuses on the Revell Site. This site is located approximately 43 km northwest of the Town of Ignace, and 21 km southeast of the Wabigoon Lake Ojibway Nation. 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.

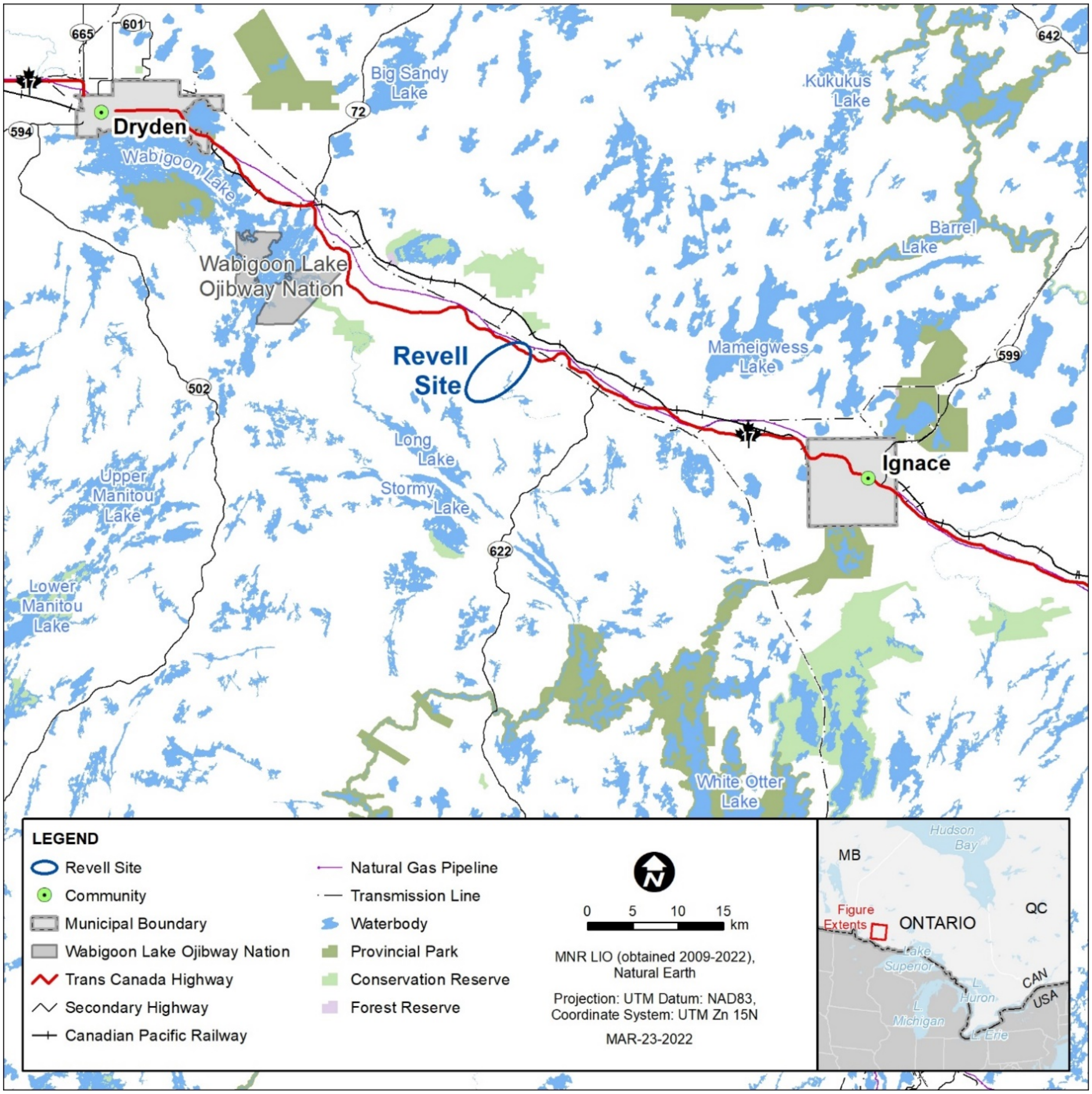

Figure 1.2: General location of the Revell Site in northwestern Ontario. Inset map shows main figure location in Ontario.

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 key components of the repository, shown in Figure 1.3 are:

- the waste form (i.e., used nuclear fuel);
- the engineered barrier systems, notably the used fuel container, buffer and sealing materials;
- 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.

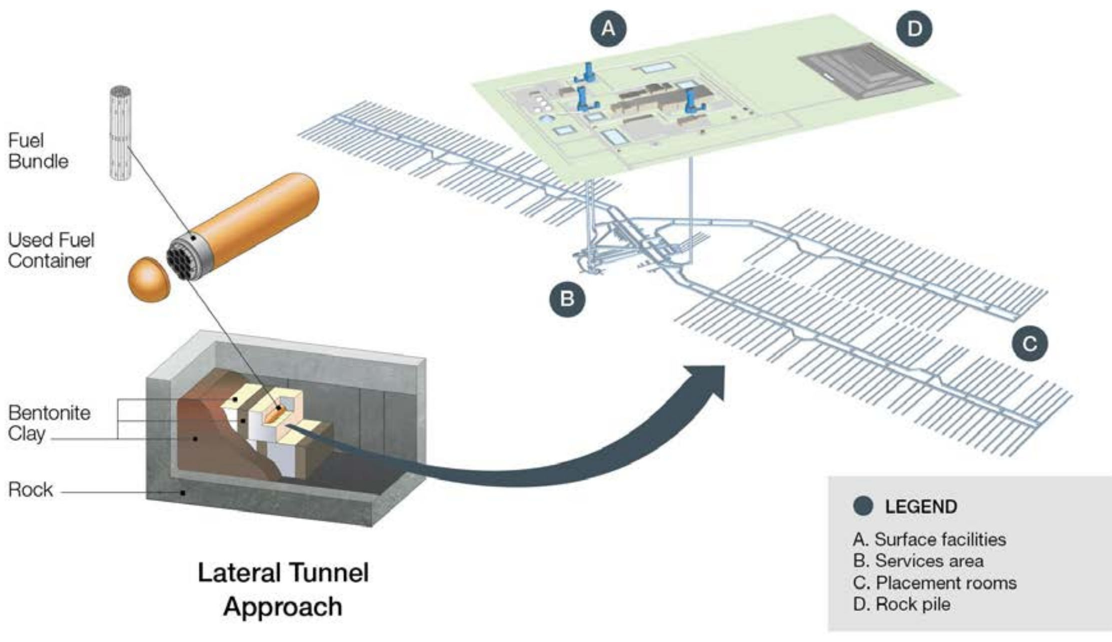

Figure 1.3: Deep Geological Repository concept

1.3 Ignace Area

The Revell Site is in the Canadian Shield in northwestern Ontario (Figure 1.1 and Figure 1.2).

The Ignace area lies in the Severn Uplands, which comprises broadly rolling surfaces of Canadian Shield bedrock that occupies most of northwestern Ontario and which is either exposed at surface or shallowly covered with glacial deposits. Terrains in the Severn Uplands contain numerous lakes and the Ignace area is typical in that regard. The land surface within the Ignace 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.

Ignace 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 Ignace area is within the Nelson River Drainage Area, which drains into Hudson Bay through the Nelson River. In the Ignace area there are three tertiary watersheds, the Upper English sub-basin, the Wabigoon sub-basin and the Central Rainy sub-basin. The Ignace 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 located in the western part of the Ignace area and is drained by the Wabigoon River to the northwest.

Water wells in the Ignace area obtain water from the overburden or the shallow bedrock. Some communities obtained 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 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 geological setting that provide containment and isolation;
- the long-term stability of the geological setting;
- 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 at around early-2022. From a site-specific data perspective, this is based on preliminary observations from site investigations over the past several years, including initial results from drilling, coring and testing of six deep boreholes at 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.

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

This report is part of a step-wise 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, 2021a). Ontario Power Generation (OPG) is now planning to build a GEH BWRX-300 Boiling Water Reactor (BWR) at its Darlington site.

The fuel for CANDU power reactors is solid uranium dioxide (UO_2) (Figure 2.1), as is the fuel for 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.

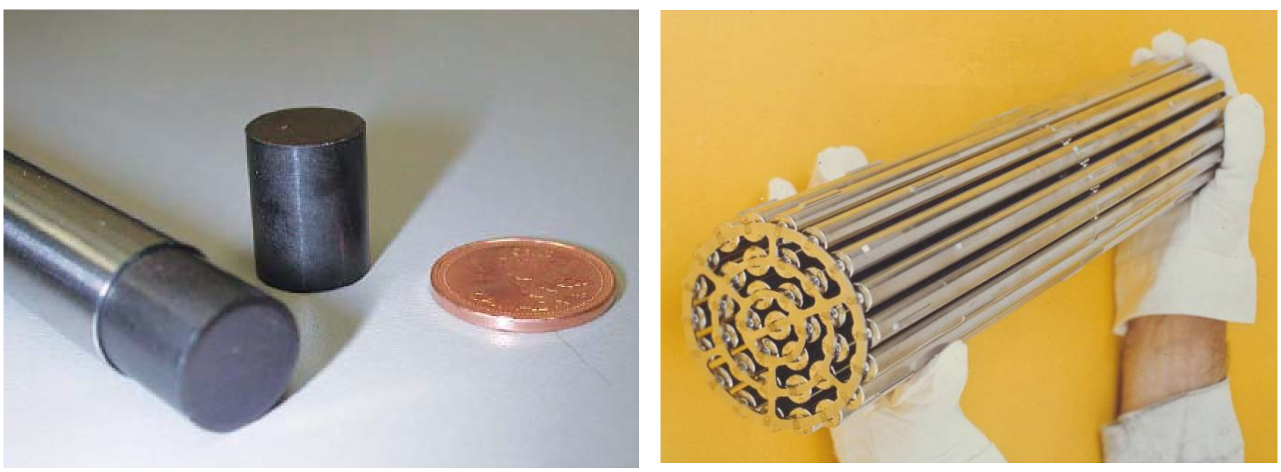

Figure 2.1: (Left) Ceramic UO_2 fuel pellets before irradiation, and pellets fitting inside Zirconium alloy cladding. (Right) Typical CANDU fuel bundle before irradiation.

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 in-reactor irradiation. This irradiation 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 mean burnup value of 200-220 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 used fuel.

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)	8.68%	8.73%
Zr-96	0.25%	0.28%
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%
Other Radionuclides	-	0.04%
Others Stable Isotopes	0.09%	0.24%

*Includes impurities naturally present in fuel

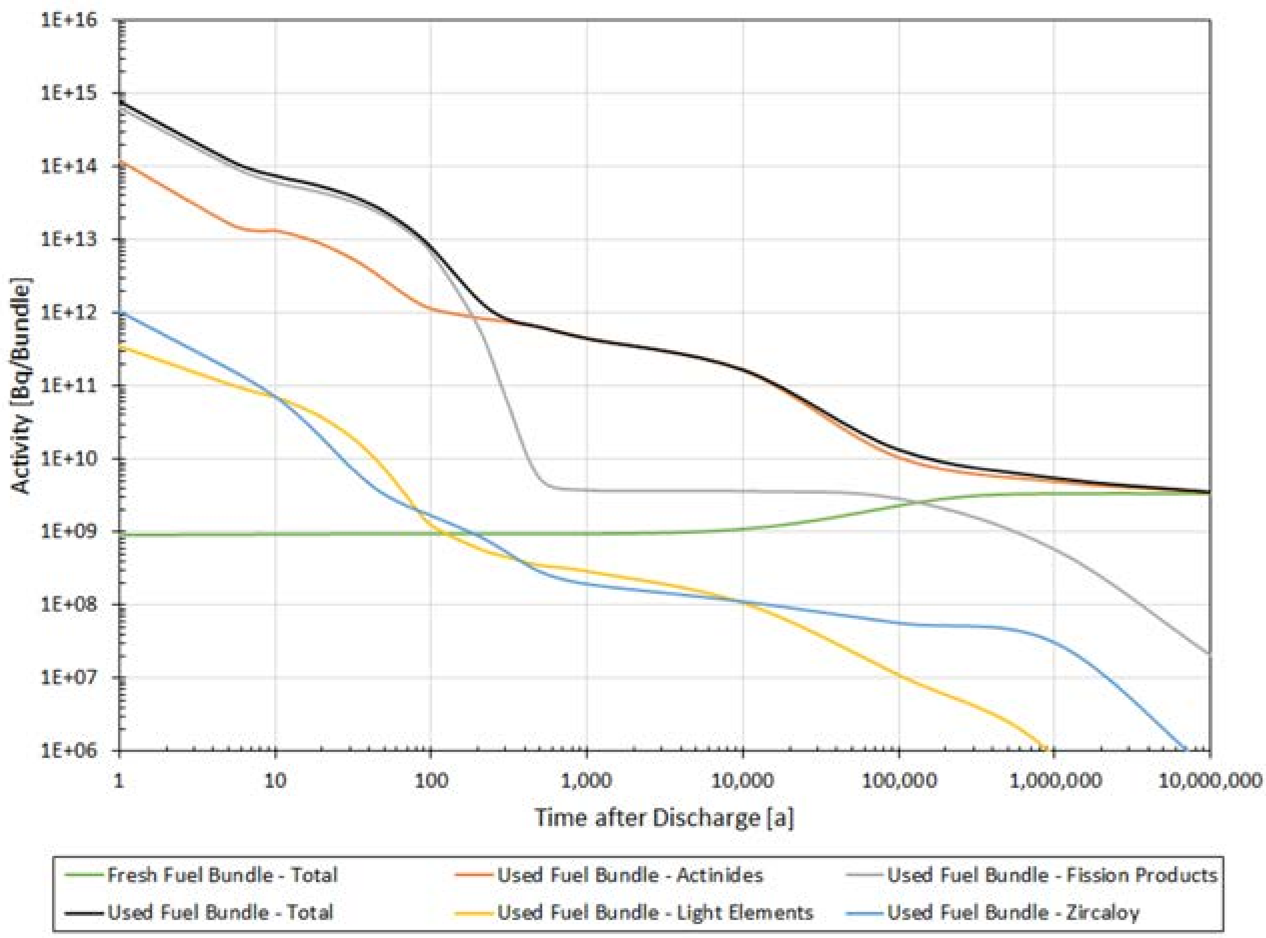

Figure 2.2: Radioactivity of used CANDU fuel decreases with time (fuel burnup of 220 MWh/kgU)

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 radiations have small ranges; thin layers of materials or air can easily stop them. In fact, the fuel bundle cladding stops most alphas and betas emitted from the used fuel.

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 provide shielding from the radiation from used fuel stored at surface.

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 multiple barrier failures, occurring before these atoms had decayed to non-radioactive atoms.

If these radioactive atoms reach the surface environment, they could expose plants, animals and humans through various pathways.

An example of hazard is the ingestion dose. In particular, it is a measure of the impact from eating food or drinking water that contains radioactive atoms, taking into account how these atoms interact with the body. 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, 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).

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 formation 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. They are informed by site characterization studies in the Ignace area 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 and geological mapping (Golder, 2017)

- 2017-2021 - Deep borehole drilling, coring and testing, and long-term monitoring, 2D seismic survey, microseismic and shallow groundwater monitoring, and additional geological mapping.

In addition, knowledge about the expected behaviour of granitic rocks, both specific to the Canadian Shield geological setting and from around the world, is used by the NWMO to develop a general understanding of the expected nature of the Revell batholith. This includes information from Canadian academic, geological survey and mining industry sources, and as well as from international academic and nuclear waste management organizations. Together with the site-specific information gathered to date, this information provides a strong basis for assessing 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 (e.g., 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 surface geology in and around the Revell Site, including the Revell batholith and surrounding greenstone belts. The Revell Site is where most of the recent NWMO 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.

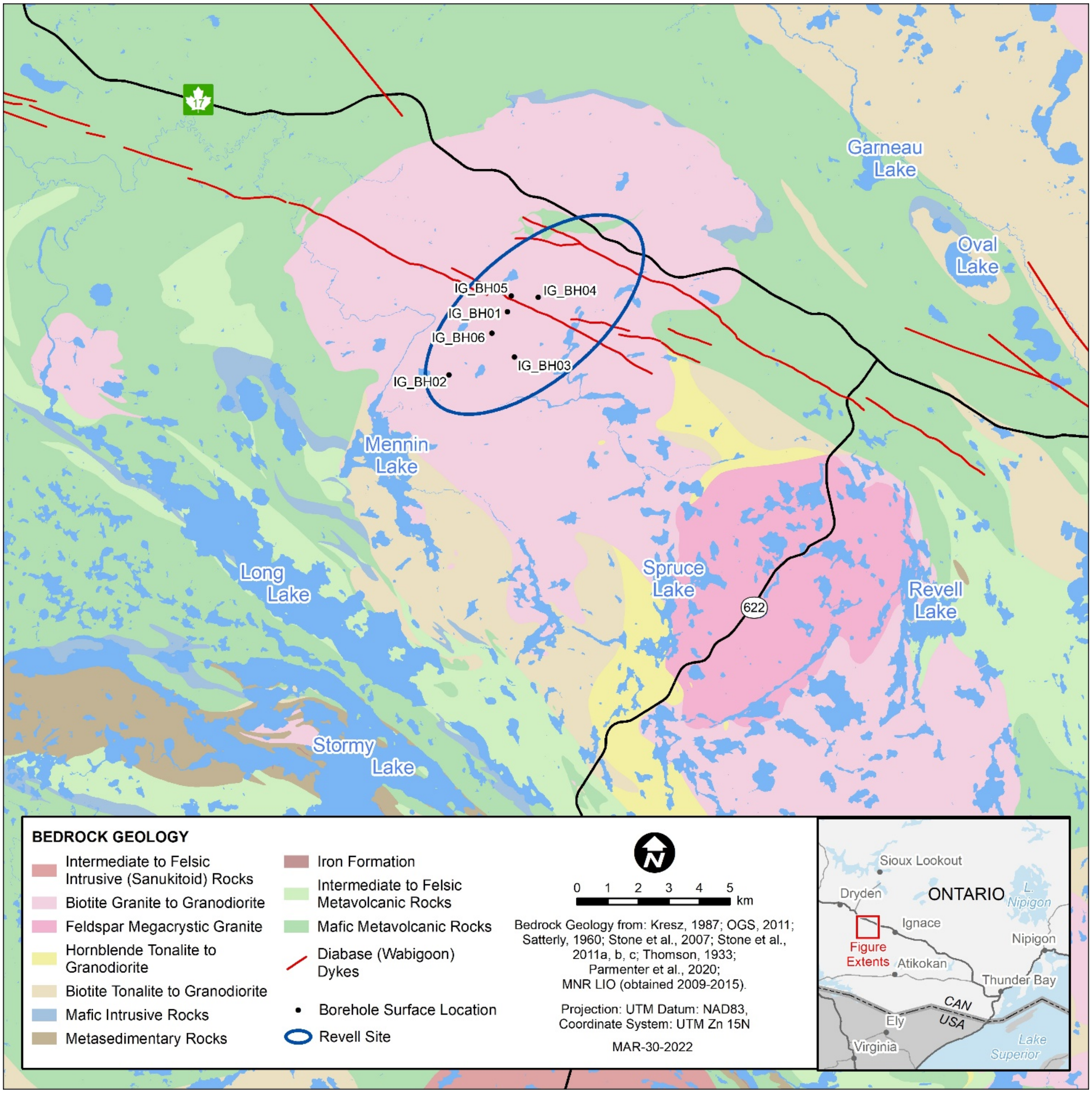

Figure 3.1: Surface bedrock map of the Revell area (Parmenter et al., 2020). The Revell Site is outlined with a blue oval.

3.2 Depth of Host Rock

The repository depth proposed for the Revell Site host rock must be sufficient to ensure safe containment and isolation of the used nuclear fuel from surface disturbances, and changes caused by human activities and natural events (e.g. logging, exploration for natural resources, surface construction, climate change, storms). A depth of about 0.5 km, within a nominal range of 0.5 to 0.8 km, is considered sufficient, depending on the geological conditions encountered above and below this depth (NWMO, 2021b).

The NWMO has developed an understanding of the depth of the Revell batholith based on the collection, evaluation, and modelling of data from:

- Mapping the surface geology within and around the Revell Site (SRK and Golder, 2015; Golder and PGW, 2017).
- Drilling and testing of six deep boreholes extending up to 1 km deep within the Revell Site.
- High-resolution airborne geophysical surveys that provide information on the subsurface geology (SGL, 2015).
- High-resolution airborne LiDAR measurements of the surface topography (ATLIS, 2018).

A 3D geophysical/geological model for the Revell regional area (SGL, 2020) has been developed based on high-resolution geophysical surveys and surficial geological data, and is illustrated in Figure 3.2. Based on current understanding, the Revell batholith has been modelled with a relatively flat base that extends to a depth of nearly 4 km 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 approximately 3 km thick. This is much deeper than would be needed to host a repository. Data collected from the first six boreholes drilled in the Revell site are consistent with the regional model and provide direct confirmation that the potential host rock, a homogeneous granitoid rock (biotite granodiorite-tonalite), extends to at least 1 km depth. The minor amount of subordinate rock types encountered in the boreholes do not appreciably impact the overall homogeneity of the bedrock. The development of a site-scale geological model which includes data from the boreholes, among other information, is currently ongoing. This site-scale model will provide a representation of the 3D geometry of the bedrock at the Revell Site itself.

In summary, based on information to date, in the Revell Site the batholith is sufficiently thick (deep) to ensure the isolation of a deep geological repository from the surface environment.

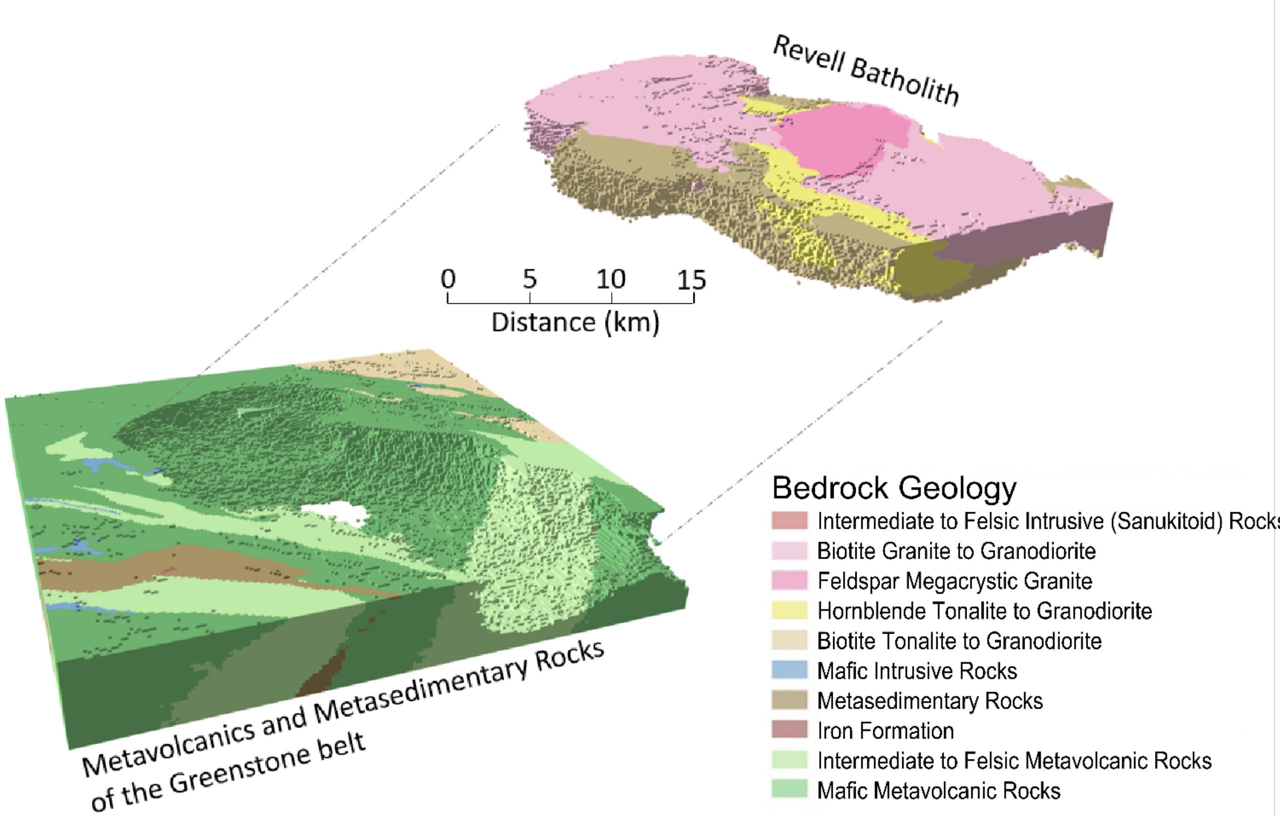

Figure 3.2: 3D regional geophysical/geological model of the Revell area. Note that the open white space in the centre of the bottom left image indicates the lower boundary of the model, at 4 km below ground surface.

3.3 Volume of Competent Rock

In addition to having sufficient depth to ensure safe containment and isolation, the host rock at repository depth should have sufficient volume of competent rock at a sufficient distance from active geological features, such as major faults, and unfavourable heterogeneities, such as regions of high groundwater flow. The hydrogeological character of the bedrock at the Revell Site will be discussed further in Section 3.5.

As discussed in Section 3.2, based on the current 3D regional geophysical/geological model (SGL, 2020) the Revell batholith is interpreted to extend to approximately 3 km depth at the Revell Site. The 3D regional model also confirms sufficient lateral extent on the batholith, providing enough 3D volume of potential suitable rock to host a repository.

Geological data at the surface, compiled during surface geological mapping campaigns (SRK and Golder, 2015; Golder and PGW, 2017), showed that the geology at surface is relatively homogeneous granitoid rock. Six boreholes drilled in the Revell Site (up to 1 km depth) have provided direct confirmation of the geology at potential repository depth and indicate that the rock encountered to approximately 1 km depth is the same relatively homogeneous granitoid rock identified at surface. Sub-horizontal to shallowly-dipping, thin amphibolite layers are evident from borehole observations and in 2D seismic data. These amphibolite layers are concentrated within a shallowly north-dipping domain and comprise less than 2% of the overall length of recovered core. The contacts between these amphibolite layers and the surrounding granitoid bedrock could be potential pathways for groundwater flow. The amphibolite also has a lower thermal conductivity than the surrounding granitoid bedrock. However, the current understanding is that, while present, these amphibolite occurrences do not significantly impact the relative homogeneity of the rock.

Geological mapping in the Revell batholith identified and characterized fractures and other planar features of different sizes at surface. Similarly, airborne geophysical and remote sensing data were used to interpret lineaments (i.e., potential fracture zones) at surface (DesRoches et al., 2018). These interpreted lineaments vary in length, with some extending for tens of kilometres across the Revell batholith. Geological mapping of several long lineaments, interpreted to represent possible fracture zones that extend into the subsurface, shows them as relatively discrete with metre-scale zones of damage to the bedrock (Golder and PGW, 2017). Geological mapping also confirmed the presence of an ancient Proterozoic mafic dyke that extends through the northern portion of the batholith. A **dyke** is a near-vertical to vertical sheet of rock that is formed in a fracture of a rock body, in this case through the intrusion and solidification of magma about 1900 million years ago. This dyke is associated with several other similarly-oriented mafic dykes in the area.

Interpreted lineaments show potential fracture zone locations at surface. 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 site investigation program is continuing to study if, and how, these features extend underground. Data from the six deep boreholes and the seismic surveys allowed for a preliminary assessment of the extension of potential fracture zones to depth. This analysis showed a relatively low degree of fracturing consistent with a relatively homogenous and sparsely fractured rock mass at the borehole locations. Interpreted lineaments, and the Proterozoic dyke, targeted during drilling were mostly encountered as intervals of increased fracture frequency within close proximity to their predicted location within the boreholes. There is no evidence from any of the data collected to date suggesting that the fractures present at depth within the Revell Site have had recent movement (faulting) or have formed in recent geological history.

The majority 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 only at depths shallower than 50 m. In each of the boreholes, the upper portion of the bedrock (about 100 m) tends to have the highest presence of moderately altered rock. Deeper in the boreholes, the proportion of moderately altered rock decreases (although is still observed locally in proximity to zones of increased fracture frequency) and the bedrock is dominated by unaltered to weakly altered intervals. Overall, at this point it is clear that whereas alteration and weathering are present, they are generally weak and have not impacted the overall competence of the bedrock.

Together the regional and site-scale studies conducted to date indicate that there is sufficient volume of homogeneous and competent granitoid rock within the Revell Site to host a deep geological repository. Taking into account 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.

3.4 Composition of Rock, Groundwater and Porewater

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

- do not compromise 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, which indicate the presence of waters containing dissolved oxygen and recently in contact with the near-surface environment, would suggest that the geological system is not able to retard radionuclide movement. Oxidizing chemical conditions would also have a negative impact (e.g., copper corrosion) on the integrity of the engineered barrier system. Total sulphide concentration in the groundwater should also be low in order to maintain the durability of the engineered barrier system. Regarding the mineralogy of the host rock, in order to contribute to maintaining the durability of the engineered barrier system, it should 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 discuss later in Section 3.6.4. 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.

As planned, groundwater samples were collected where possible from water-bearing fractures intersecting the six boreholes drilled to date and sent to laboratories for geochemical analysis. Information on the geochemical composition of water at depth was also obtained from the minute amount of less mobile porewater extracted from core samples collected at different depths. 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, with the relatively shallow rock units (less than about 400 m depth) dominated by Ca-HCO_3^{2-} and transitioning (about 400-700 m depth) to a higher salinity Ca-Na-Cl (-HCO_3^{2-}) composition toward the base of all boreholes. Based on the results from the groundwater and porewater samples that have been analyzed to-date, the waters at depths below 500 m likely have very long underground residence times on the order of hundred of thousands to millions of years, and oxidizing conditions are not observed.

For all groundwater samples collected during drilling to-date, the total dissolved sulphide concentrations were very low, below the method detection limit of 0.02 mg/L. Based on data available to date, these low sulphide concentrations in the groundwaters at the site are not likely to impact the durability of the copper within the engineered barrier system.

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 biotite granodiorite-tonalite, referred to throughout the remainder of this report as **granodiorite-tonalite**. The remainder of the recovered core comprises subordinate rock types, including amphibolite and several distinct suites of felsic dykes. Mapping data confirms this homogeneity and lithology at surface. 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 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 exhibit low porosity, which is to be expected in these types of igneous 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. The average connected and total porosity of the amphibolite 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.

There are no indications from the sample 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. The discussion of the favourable retardation properties of the rock are also continued in Section 3.5 below.

3.5 Hydrogeological Regime

To retard or 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 must 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 property **permeability**). The larger the value of hydraulic conductivity, the more easily water can move through the rock.

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, which is an indirect indication of groundwater velocities of the host rock at subsurface. For the six boreholes drilled to date, there were only four instances below 100 m depth where groundwater was able to flow into the borehole at levels sufficient to collect groundwater samples during drilling.

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

At potential repository depths (500–800 m) in the Revell Site, the hydraulic conductivity values estimated for the rock mass have a median value between 10^{-13} and 10^{-12} m/s. These values are from the first three boreholes, with final data from the latter three boreholes still pending; preliminary results indicate that the hydraulic conductivity data for the subsequent boreholes are consistent. For comparison, the hydraulic conductivity of pure sand ranges from 10^{-6} to 10^{-2} m/s; the estimated rock mass hydraulic conductivities at the Revell Site were over a million times smaller. In tested borehole intervals that were interpreted to represent flowing fractures, the hydraulic conductivity ranged between 10^{-12} and 10^{-6} m/s. In these intervals the fracture intensity was usually increased and, commonly, there was presence of a subordinate rock type.

One of the key reasons for undertaking these tests is to investigate variation in hydraulic conductivities with depth at the Revell Site. Researchers at University of Waterloo (Snowdon et al. 2021) have recently compiled permeability data from seven research sites across the Canadian Shield, including batholiths and other rock formations. 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 representative elementary volume of rock consisting of rock matrix and brittle structures with no observed flowing conditions. The results indicate a general pattern for decreasing permeability with depth for both EPM rock mass and fracture data. Hydraulic conductivity data estimated for the first three boreholes at the Revell Site are consistent in their distribution in comparison to the data of Snowdon et al. (2021), and are within the range of the broader Canadian Shield data. Preliminary results for the next three boreholes indicate that estimated hydraulic conductivities are also consistent with Snowdon et al. (2021). Overall, hydraulic conductivity values estimated for the EPM rock mass at the Revell Site indicate the potential for low groundwater velocities.

Following the completion of drilling and downhole testing in the first two boreholes, multilevel monitoring systems were installed. These systems permit long-term measurement of pressures and collection of groundwater samples from intervals in the borehole. Preliminary interpretation of pressure distributions in these two boreholes indicate the presence of increasing groundwater fluid density at depths below ~600 m at the Revell Site, suggesting increasing salinity in the water. The presence of increasing salinity, as shown in Park et al. (2009), can indicate a hydrogeologically stable environment at depth. Multi-level monitoring systems have also been installed in the last two deep boreholes drilled at the site.

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.

3.6 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, granitic 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. These are discussed below.

Rock Mechanical Properties

To date, data on the strength of intact samples are mainly based on laboratory testing of core samples of the main rock type (granodiorite-tonalite) from the first three boreholes, and limited laboratory testing of subordinate rock types present in small amounts such as amphibolite. Further measurements are underway on core samples from boreholes four to six. Direct shear tests are also underway to determine shear strength properties of rock fractures mainly from fractured granodiorite-tonalite samples from boreholes four to six.

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 3.3). 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 of 225 MPa. The subordinate rock types had mechanical properties within approximately the same order of magnitude as granodiorite-tonalite; for example, amphibolite samples 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 are similar to those of similar rock types elsewhere in the northwestern Ontario (e.g., Stone et al., 1989).

Figure 3.3: Example of an intact, three-metre long, section of drill core displaying the low fracture frequency typical of the Revell Site.

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).

While analysis of this data is still ongoing, preliminary results indicate that overall, the rock mass properties for the Revell Site are similar between the first three boreholes, and data is still pending for the latter three boreholes. 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).

Typical broken fracture spacing observed from the first three boreholes drilled to date 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 fracture spacing increases to greater than 3 m. Fracture frequency tends to increase in sections containing subordinate rock types.

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%. The RQD values in the first three boreholes generally indicate that the biotite granodiorite-tonalite, which represents approximately 97% of the recovered core, is ‘excellent’ quality rock.

Overall, the rock studied to date has a low level of both alteration and weathering, which could impact rock strength, and the fracture frequency per metre is low. These conditions indicate a strong rock mass. Although the rock mass classification index determination is ongoing, preliminary indications are that the rock mass properties in the Revell Site are typical of high quality crystalline rocks.

Bedrock Stresses

Bedrock stresses are measured underground, for example in a borehole, and represent 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 are planned for the Revell Site.

Preliminary repository layouts are being developed for the Revell Site considering information available for the Canadian Shield (Yong and Maloney, 2015); during detailed site characterization site specific stress measurements will be taken to refine the repository layout. At this stage information available 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 these damages can be indicative of the local stress fields.

At the Revell Site, several borehole breakouts were identified in four out of the first six boreholes. These breakouts occurred at depths ranging between approximately 600 m and 950 m. This is not unexpected at depth in the 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). Site-specific stress magnitudes and orientations will be confirmed in future investigations.

Thermal Properties

The host rock should be capable of conducting away the residual heat generated from the used fuel containers, and withstanding thermal stresses induced by this heat, without significant structural deformations or fracturing that could compromise the safe containment and isolation functions of the repository.

Preliminary thermal conductivity, thermal diffusivity, and volumetric heat capacity data are based on laboratory testing of core samples of the main rock (granodiorite-tonalite) and limited testing on subordinate rock types, such as amphibolite, 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 at room temperature was measured at 2.64 W/m.K.

Based on the preliminary data, the thermal properties of intact rock in the Revell Site are similar to those of equivalent rock types elsewhere in northwestern Ontario. Revell Site thermal conductivity values for the biotite granodiorite-tonalite, in particular, are also comparable to those of granite, granodiorite, and tonalite as measured in the crystalline rocks of the Forsmark site in Sweden, which is also planned to host a repository for used fuel (SKB, 2007).

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.

This preliminary data indicates that the Revell Site host rock is capable of removing the decay heat from the fuel and withstanding thermal stresses induced by the repository.

Host Rock Geomechanical and Thermal Summary

The rocks of the Revell batholith are similar to those of other crystalline rocks of the Canadian Shield. They are relatively predictable and not unusual in their mechanical and thermal behaviour, enabling them to be confidently characterized and modelled. They 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). Figures 4.1 and 4.2 show seismic activity for northern Ontario as recorded by the Canadian Hazard Information Service between 1985 and 2021. Earthquakes are measured using the Nuttli Scale (m_N), developed for Eastern North America, which represents a modern refinement of the older Richter scale. To date 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 microseismic monitoring stations was installed around the Revell Site. These nine stations will provide increased ability to identify and locate smaller earthquakes within a 50 km radius of the site. This microseismic network will continuously record seismic events in the long term. Monitoring of earthquakes, even small magnitude events (magnitude 3 m_N and lower), will provide information on the overall seismicity and geological structure of the region. Ground vibrations associated with these small magnitude events are below the threshold considered to be able to cause structural damage to buildings.

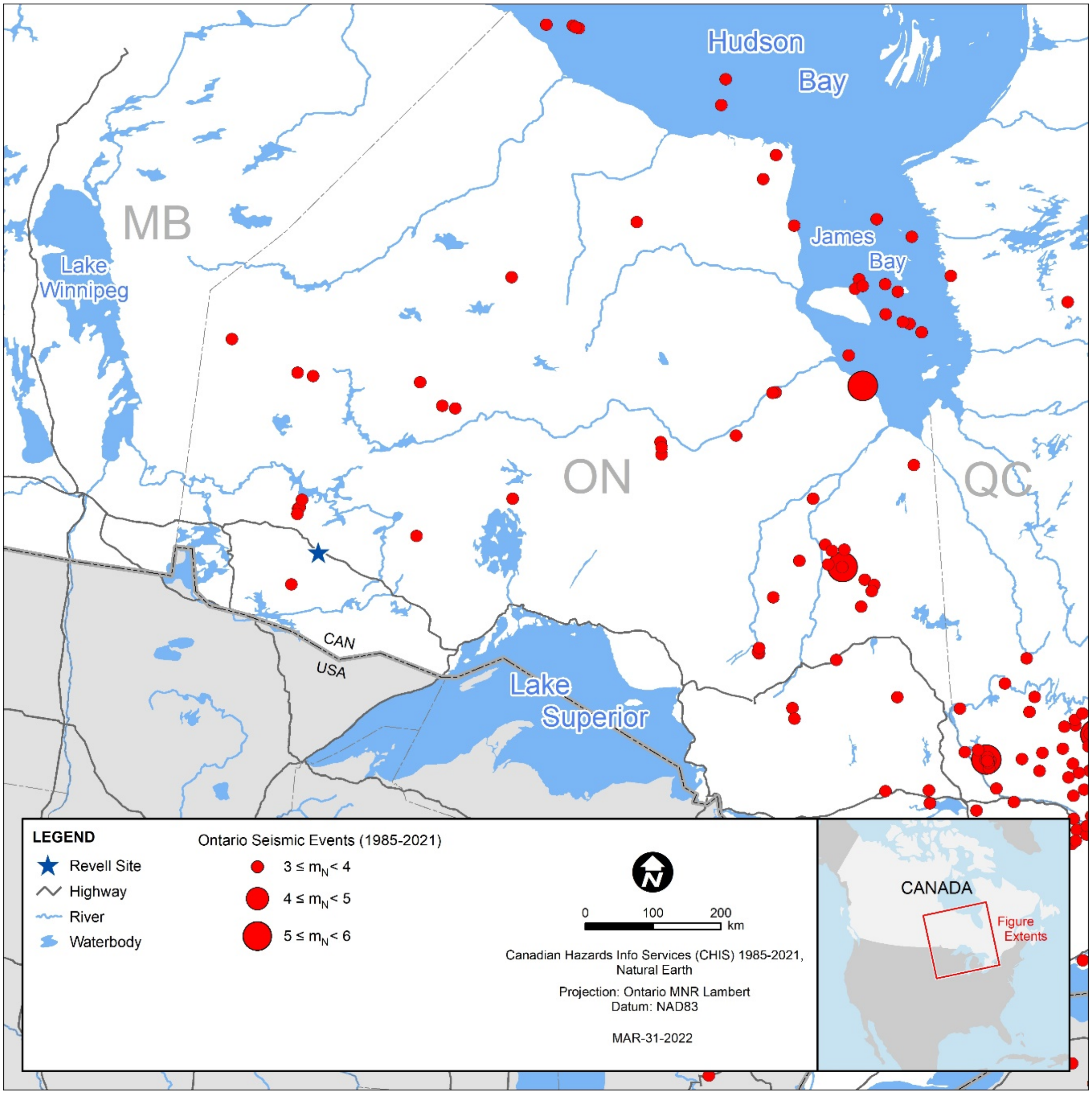

Figure 4.1: Earthquakes with Nuttli magnitude (m_N) greater or equal to 3 in northern Ontario, 1985–2021.

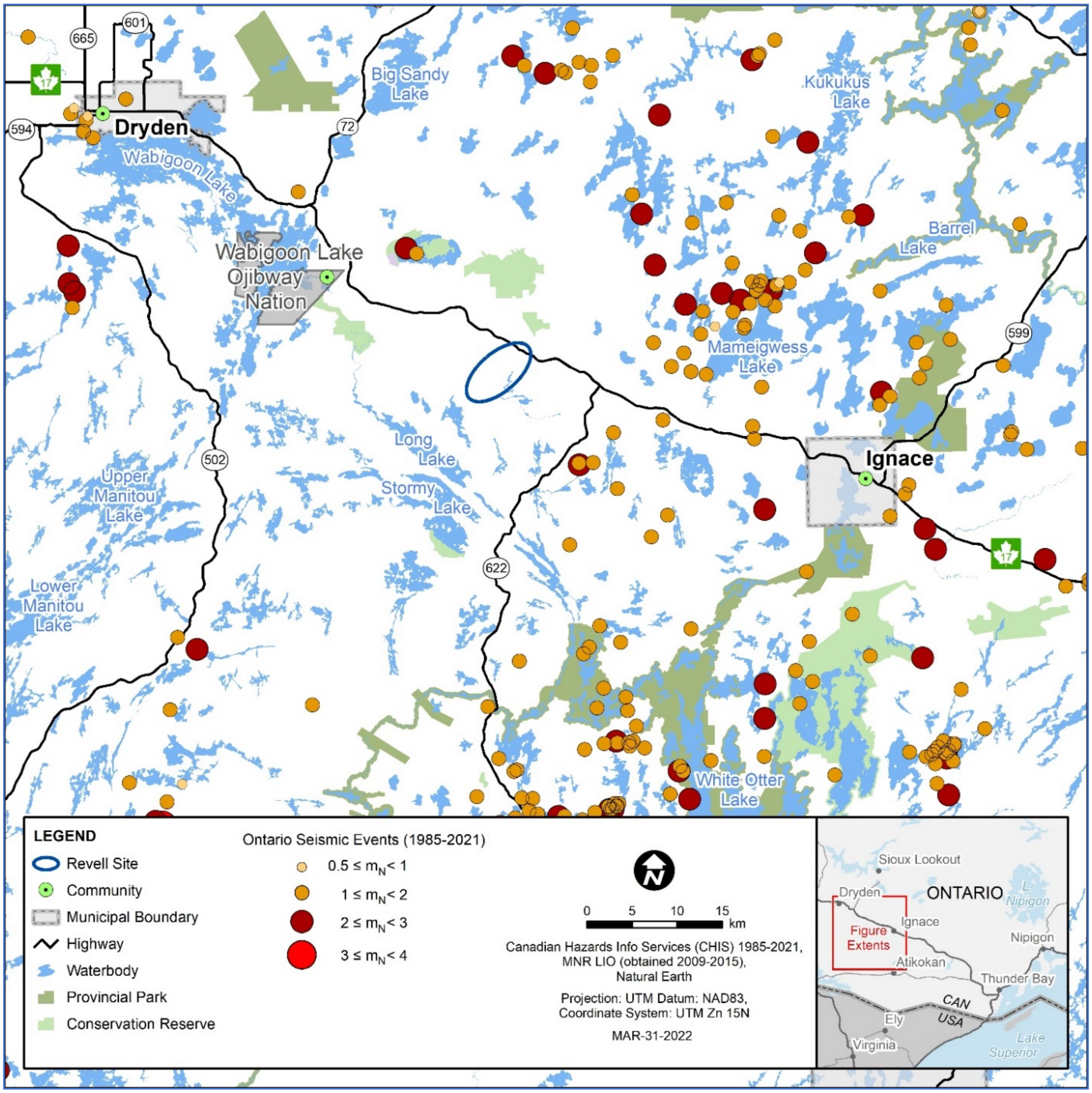

Figure 4.2: All seismic activity recorded around the Revell Site since 1985.

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 land uplift, subsidence, and erosion. Land uplift, subsidence, and erosion in the Canadian Shield where the Revell Site is located are expected to be mostly related to future glacial cycles (Robin et al. 2020). The bedrock in the Ignace area is presently uplifting at 3-5 mm per year, as the continental rock slowly recovers from the last ice age (Sella et al. 2007). The rate at which these processes occur in the future will need to be sufficiently slow to ensure that the repository remains isolated from the surface environment over the long term.

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) estimates 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 northwestern 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 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 100,000 years for the past million years, largely due to the nature of the earth's orbit around the sun. The last ice age started about 100,000 years ago and ended about 10,000 years ago, when the ice retreated out of Ontario towards northern Canada. During an ice age, 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 water from future ice sheets does not penetrate to repository depth; the presence of oxygenated 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. Based on previous analyses, the evolution of the conditions at repository depth during future climate change scenarios such as glacial cycles should not have a detrimental impact on the long-term safety of the repository (NWMO, 2017).

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. In addition, the trends in both the groundwater and porewater chemistry profiles with depth in the boreholes drilled to-date imply stable and consistent hydrogeological conditions at repository depths throughout these past glacial cycles.

Future ice sheets should also not have a negative impact on the geomechanical stability of the repository. During past glaciations, ice sheets over where the Revell Site is located were up to 2.5 km thick; 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 emplacement 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.

Based on information obtained to date, there is no evidence that the evolution of the conditions at repository depth during future climate change scenarios such as glacial cycles will have a detrimental impact on the long-term safety of a deep geological repository at the Revell Site.

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. These important geological features include regional structures that are up to hundreds of kilometres in length. These geological features are interpreted to have formed originally during the Archean stage of amalgamation of the Canadian Shield approximately 2700 million 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 within the western Wabigoon Subprovince 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.

Within the Revell Site, lineaments at surface have been interpreted (i.e. identified or inferred to be present) that may represent potential fracture zones in the bedrock. Despite these features being interpreted, it is possible that some of these lineaments either may not extend deep into the subsurface or may only represent undulations of the surface morphology and not fracture zones. Because fracture zones represent an important potential groundwater flow pathway, or loci for future seismic reactivation, they will continue to be assessed through future site investigation activities (e.g. borehole drilling and testing, field mapping and geophysical surveys).

In addition, the on-going microseismic monitoring will aid in identifying the presence of any active faults in the regional area surrounding the Revell Site.

5. FUTURE HUMAN INTRUSION

The site should be selected such that the repository is not likely to be disrupted by future human activities that could compromise the containment and isolation of the fuel. For example, future societies should not have reason to inadvertently drill into the repository.

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

1. Should not be located within rock formations 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 formations containing groundwater resources at repository depth that could be used for drinking, agriculture or industrial uses.

Each of these are 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, given their genesis, are not encountered in crystalline environments. Economically exploitable natural resources in the Canadian Shield are mainly limited to mineral resources.

Generally speaking, relatively undeformed granitic 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 southeast of the Revell batholith (Figure 5.1). The mining claims that extend across the southeastern 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 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 above the proposed repository volume at the Revell Site.

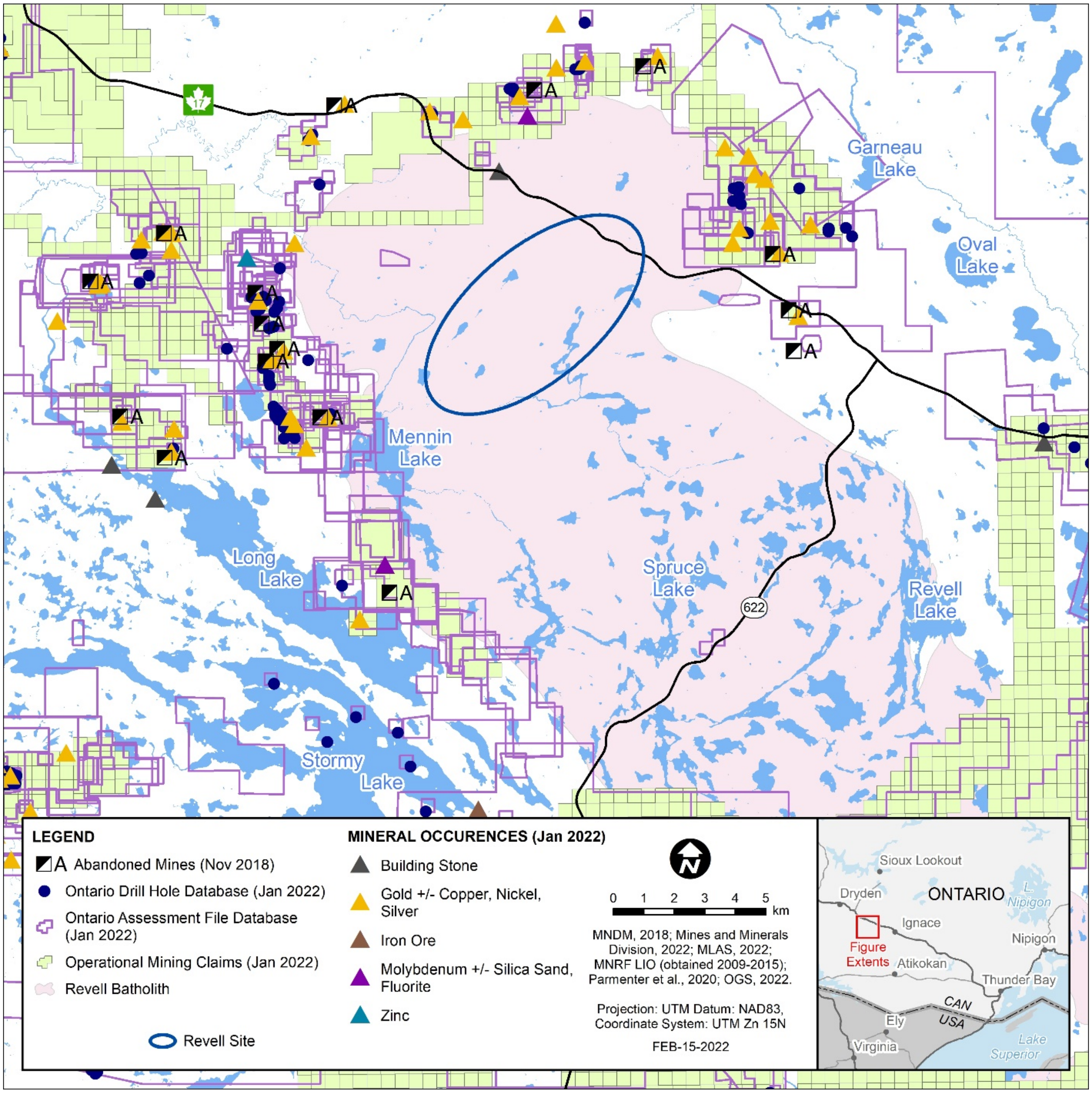

Figure 5.1: Locations of abandoned mines, operational mining claims, mineral occurrences, and exploration work in the vicinity of the Revell Site.

5.2 Groundwater Resources

As described above in Section 3.5, hydraulic conductivity 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 rock mass hydraulic conductivity values are too low to result in exploitable groundwater resources, i.e., the rock at depth cannot supply significant amounts of water. Furthermore, rock core measurements indicate very low porosity in the intact rock. Hydraulic conductivity estimated from packer testing of flowing fracture zones at the Revell Site varies from 10^{-12} m/s to 10^{-6} m/s.

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).

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 hydraulic conductivity of 10^{-6} m/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, however, 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 adapted and 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 geometry and structure are relatively predictable and can be reliably characterized.

The Revell Site was selected for study, including borehole drilling and testing, 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, through borehole drilling and testing, additional field mapping, and 2D seismic surveying, has confirmed the relatively predictable nature of the site based on the following:

- Uniformity of the subsurface bedrock, with over 95% of the 6 km of recovered core identified as granodiorite-tonalite rock with relatively consistent mineralogy.
- A relatively low fracture frequency along boreholes, and limited hydraulically-conductive features, consistent with a relatively homogenous and sparsely fractured rock mass at the borehole locations.
- Locations where amphibolites are encountered follows a predictable pattern in the subsurface.
- Inferred fracture zones, and the Proterozoic dyke, targeted during drilling were mostly encountered as intervals of increased fracture frequency within close proximity to their predicted location within the boreholes. In some cases, the inferred fracture zones did not display any evidence of having fracture zone type properties such as, for example, increased fracture intensity.
- Preliminary assessment of the 2D seismic survey results present subsurface images that show subhorizontal high-amplitude reflections interpreted as amphibolites in a north-dipping geometry that is consistent with results from the boreholes.
- Many hydrogeological, hydrogeochemical, and rock mechanics properties are consistent with relevant data from other similar Canadian Shield locations.

These studies 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, 2021b).

The following sections elaborate on the current 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), with the nominal dimensions described in Table 7.1 and illustrated in Figure 7.1 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. 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).

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. For example, the container copper coating process technology has been developed to allow the coating thickness to tailored to the site-specific requirements (i.e., increased or decreased).

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

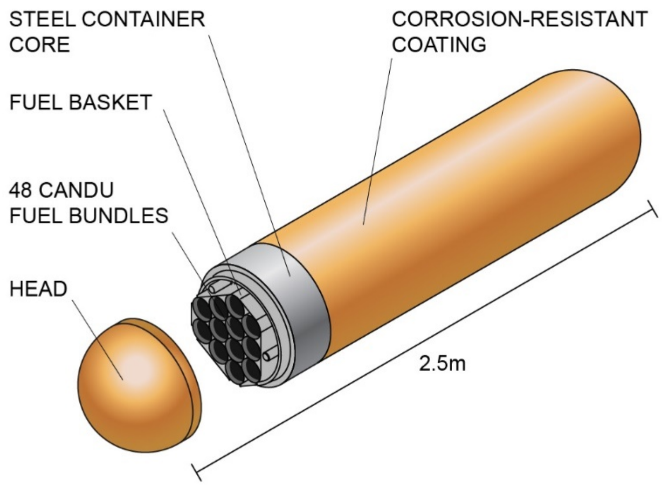

Figure 7.1: Illustration of reference copper coated Used Fuel Container

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. More information is provided on international waste management organizations that are pursuing geological disposal in Section 11.

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 is planning to submit an application to build a GEH BWRX-300 BWR at its Darlington site. The BWRX-300 fuel is similar to the light water reactor fuel that Posiva and SKB manage.

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. NWMO will leverage and build on the reference CANDU fuel container, as well as, international container designs developed for these fuel types.

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 greatly 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 emplacement activities underground. The upper and lower halves of the bentonite are known as the **buffer box**, as shown in Figure 7.2.

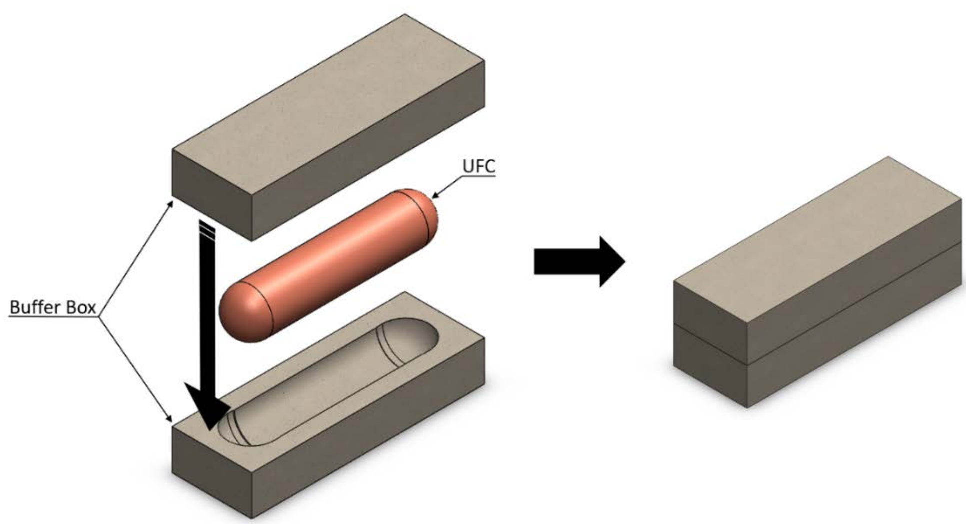

Figure 7.2: Used Fuel Container within a bentonite clay Buffer Box

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 emplacement. 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.

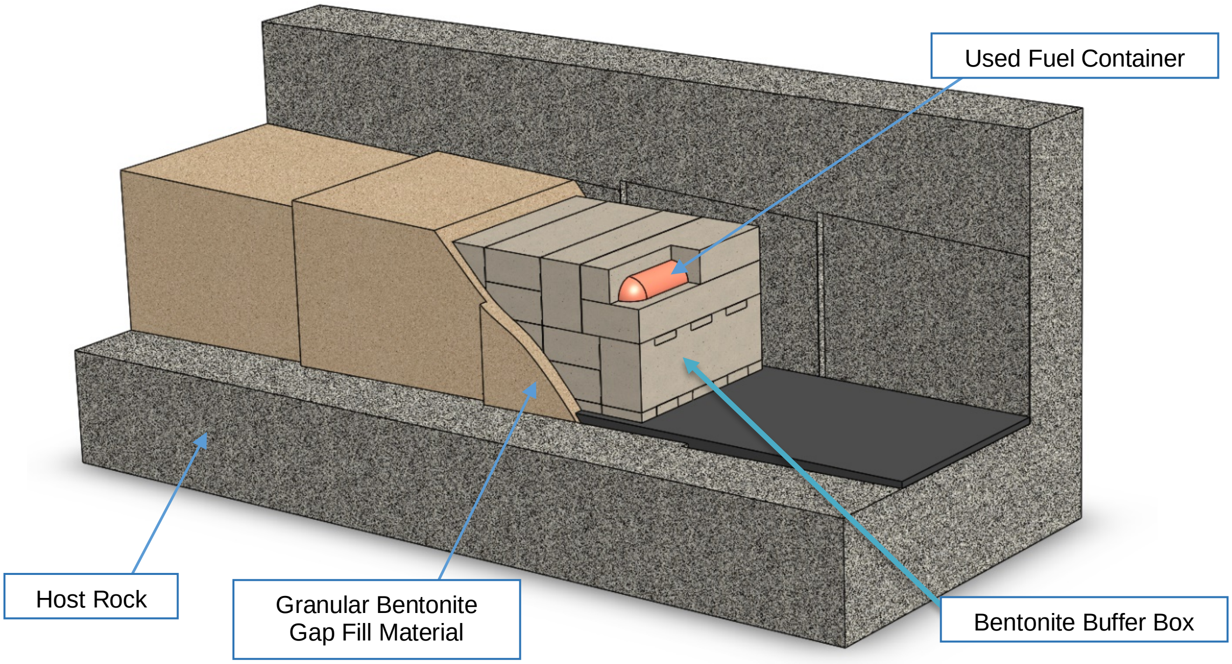

Figure 7.3: Cutaway illustration of emplacement room concept

The ends of the emplacement 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 emplacement underground for all of Canada's projected used nuclear fuel (NWMO, 2021a). 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. 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 emplacement 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. The use of proven technologies and consistency with international best practices provides confidence that the design will be successful.

To build on that confidence, an experimental and 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 components and their emplacement.

At the end of 2021, the NWMO has finalized the reference CANDU fuel container and bentonite fabrication and inspection processes including all supporting equipment. These processes have been successfully used to create full-scale container and bentonite buffer box prototypes. This is described further below.

<u>Container Fabrication and Testing</u>

As of early 2022, the NWMO has fabricated six full-scale containers, with several partial containers in various stages of manufacturing. A total of 15 containers are planned by the end of 2022. The prototyping process has resulted in improved fabrication methods, full-scale demonstration of inspection methods, and allowed various structural tests to be performed.

The program started with small scale samples 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. Recently they have also been 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.

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. The containment boundary remained intact in this test.

Another key test was full-scale container testing at the Applied Research Lab at Penn State University, as shown in Figure 7.5. A container was placed into a test chamber where it was subjected to hydrostatic pressure equivalent to being almost six km underwater. This pressure exceeds the maximum total pressure expected in the repository, including up to a three-km thick ice sheet rock above the repository during the next ice age by about 20%. This bounding loading condition, well above the container design basis, was selected to confirm that the container initial yield stress and buckling (e.g., crushing) occurred when expected from the computer modeling. The testing confirmed the container can withstand the maximum repository pressure loads without any permanent change and that the modeling was accurate.

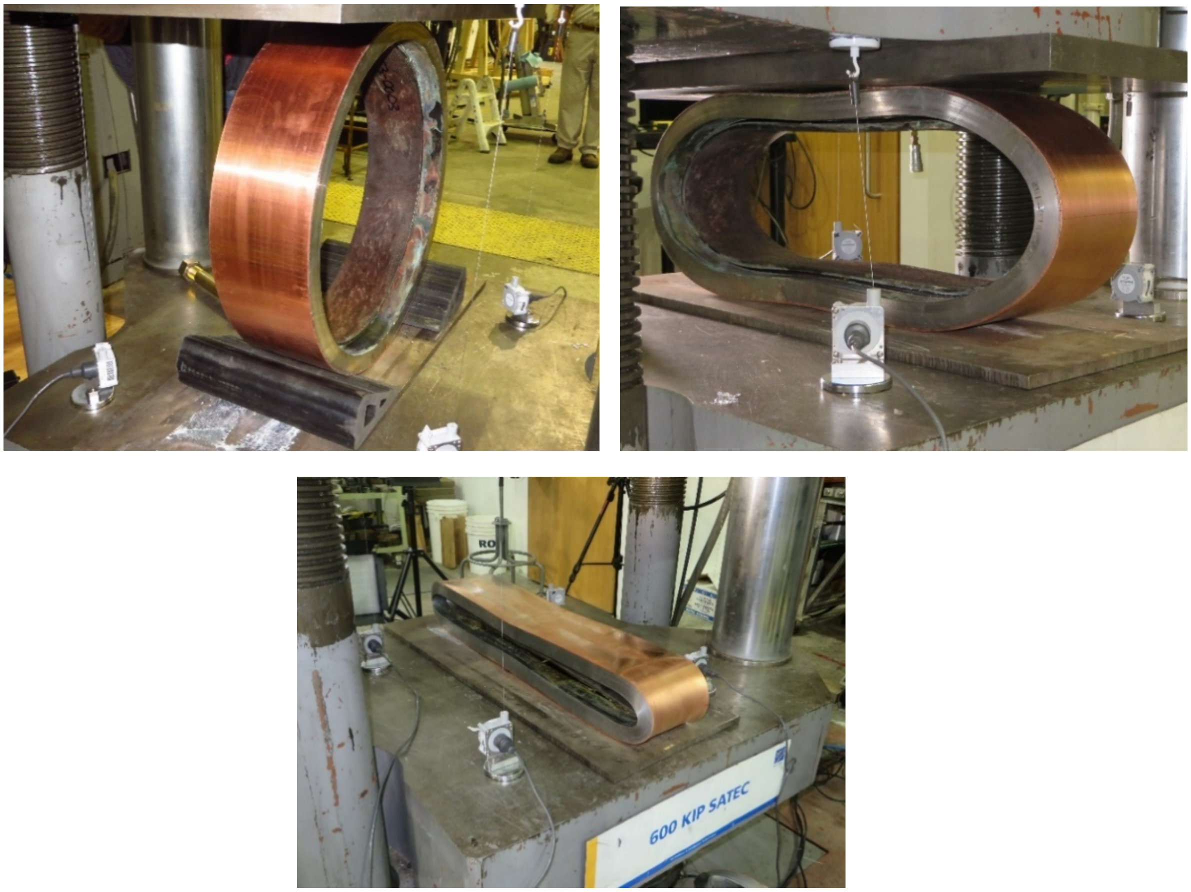

Figure 7.4: Used Fuel Container cross-section undergoing a beyond-design-basis crush test. Copper coating remained bonded to steel.

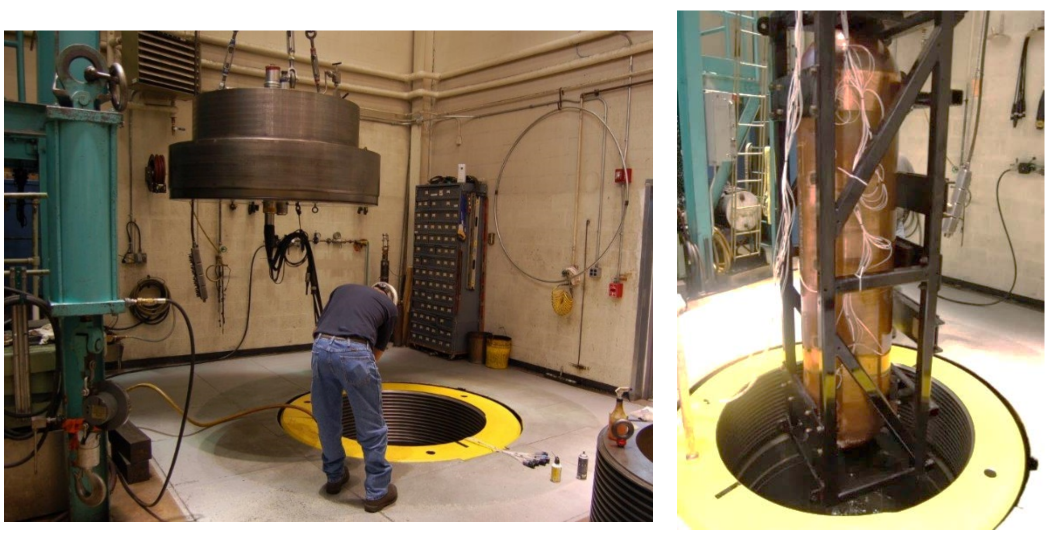

Figure 7.5: Prototype Used Fuel Container subjected to external pressure equivalent to almost 6 km underwater. (Left) Test chamber lid being lowered into place; (Right) Container removed after testing; fully intact – no containment failure.

Buffer Fabrication and Tests

As of early 2022, fabrication of more than 10 buffer boxes have been completed, as shown in Figure 7.6, 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 7.7.

Figure 7.6: Prototype Buffer Box and Used Fuel Container

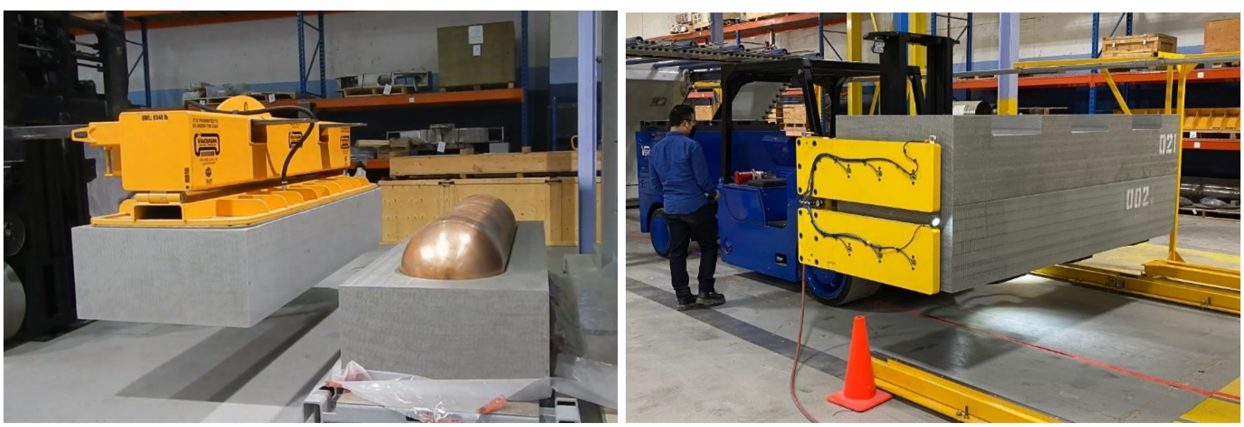

Figure 7.7: Bentonite handling: (Left) Using vacuum lift technology; (Right) Robotic forklift handling of buffer box

<u>Emplacement Test</u>

The NWMO has manufactured a full-scale mock emplacement room, complete with faux-rock walls with simulated drill-and-blast excavation profiles. The program has designed, manufactured, and performed initial testing on all the required emplacement equipment as shown in Figure 7.8.

In 2022, the NWMO will conduct the full-scale emplacement trial using the prototype components and emplacement equipment. The emplacement operational procedures will be tested, and lessons learned documented. The emplacement room will be partially disassembled and inspected to see if the emplacement meets the performance requirements.

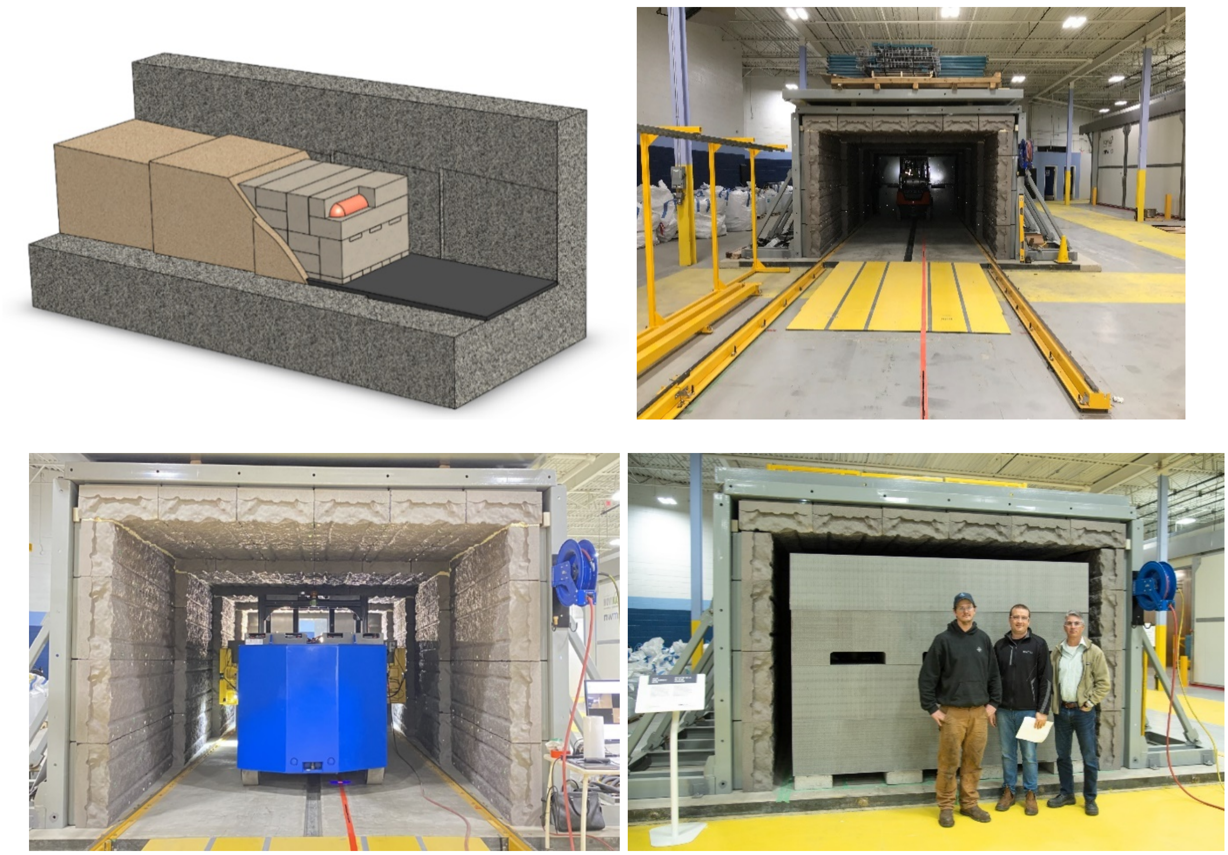

Figure 7.8: (Top left) Emplacement room concept; (Top right) Full-scale mock emplacement room at NWMO Test Facility; (Bottom left) Emplacement machine travelling inside room; (Bottom right) Stacked buffer boxes.

7.2 Underground Facilities

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.

Access to the underground is provided via three shafts:

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

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.

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. Specific attention would be given to avoiding major fracture zones, through knowledge of fractures from surface studies, and through drilling pilot holes before excavating in key areas. By using these methods, suitable rock for placement rooms will be ensured.

A conceptual repository layout for a hypothetical crystalline rock site using the adaptive layout design approach is shown in Figure 7.9. This is not the Revell site layout; a site-specific underground layout for the Revell is under development this year and will incorporate available field investigation data. As of early 2022, layout development has confirmed that the Revell has sufficient land available to establish an adaptive layout for the current used fuel projections considering preliminary field data (NWMO, 2021a).

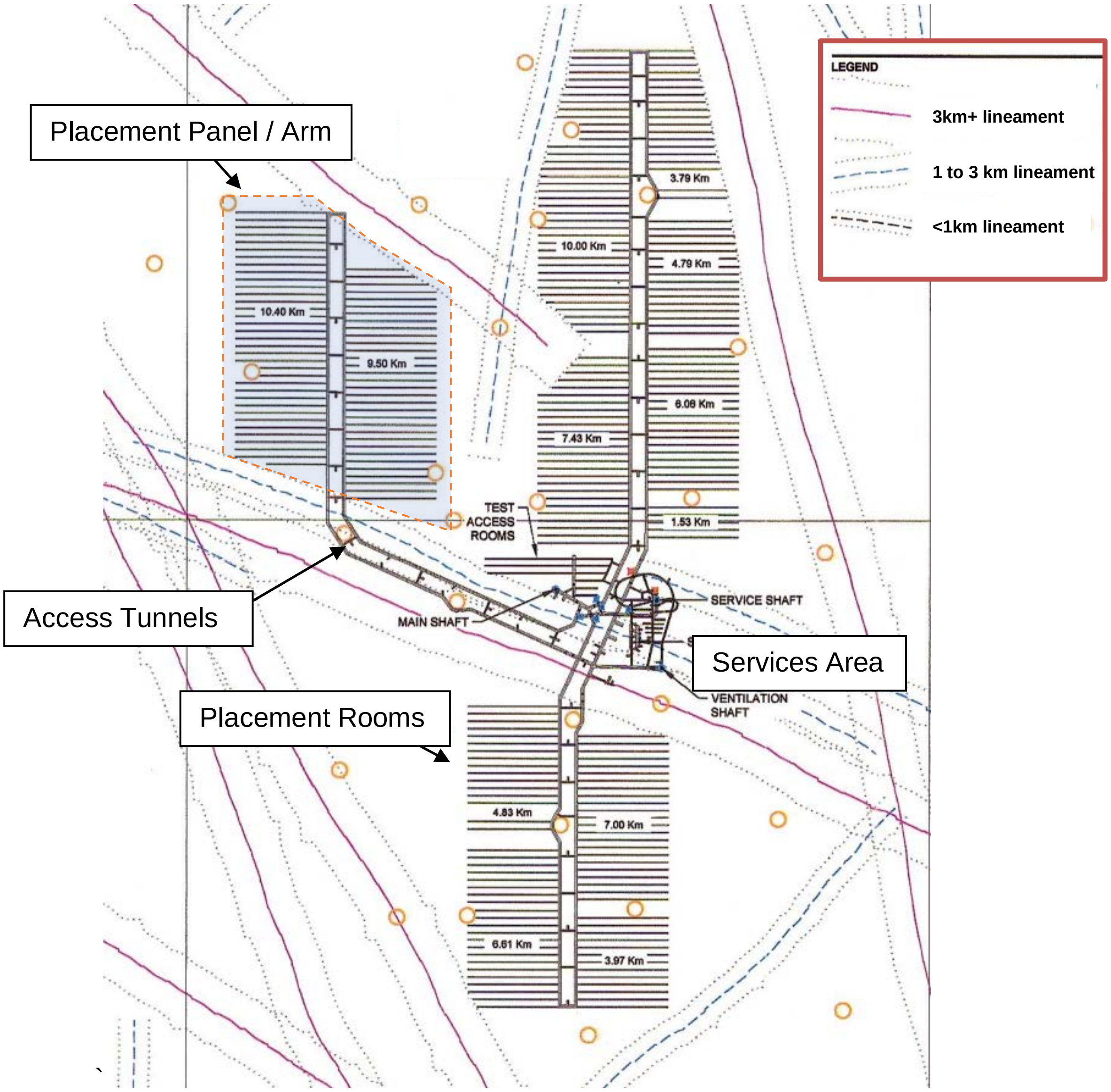

Figure 7.9: Conceptual underground repository layout for a hypothetical crystalline rock site, showing services area, access tunnels, placement arm panels, and emplacement rooms. Lineaments and layout are for illustration purposes only and do not reflect the Revell site conditions.

The placement rooms are 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. 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.

Based on the current nuclear fleet in Canada and planned refurbishments, the repository would contain approximately 5.5 million used fuel bundles within approximately 120,000 containers (NWMO, 2021a). The repository area is about 6 km^2.

The mechanical properties of the rock are important to the repository design. The reference repository depth is planned for 500 – 800 m; the final repository depth will be informed by detailed site characterization. For the crystalline rock at the Revell Site, excavation of the underground openings at this depth range does not represent a technical problem. 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.

The NWMO's current reference plan is that the three shafts will be developed using conventional controlled drill and blast. As the site investigation and the construction plan advances, other shaft excavation techniques (e.g., raise bore excavation) will be considered. The design of the shaft liner and grouting system will be completed after the location of the shaft (and site) is established. The shaft liner will serve two purposes; first it is a measure of ground support, preventing minor ground shifts or loose rock from falling into the shaft, and second it will act as a means to prevent seepage of water in the shaft.

During emergencies, 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. In cases where 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 emplacement activities are occurring. They are also fully sealable and use compressed air bottles for emergency breathing air. They will be stocked with similar safety equipment and rations as the permanent refugee station.

Another system important for mining safety is underground ventilation. The system uses a series of surface fans, underground booster fans, ventilation doors, and regulators to control airflow distribution and 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 on surface 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, such as underground fire or radioactivity being detected in the underground air at above-background concentration levels.

7.3 Surface Facilities

A description of all surface and underground facilities is provided in the 2021 DGR conceptual design report (NWMO, 2021b). A conceptual layout for the surface facilities is shown in Figure 7.10.

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.

A description of all surface and underground facilities is provided in the 2021 DGR conceptual design report (NWMO, 2021b). The following sections discuss the key facilities with the potential to cause environmental impacts (i.e., water and air emissions) and the technology or processes that will be used to eliminate or mitigate these impacts.

Figure 7.10: Illustration showing conceptual DGR surface facility layout

Site Security

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.

Used Fuel Packaging Plant

The Used Fuel Packaging Plant (UFPP) facility receives the used fuel transport package, opens the 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.

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 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.

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 taken for disposal off-site following all applicable regulations.

Site stormwater run-off will be collected and diverted to several stormwater managements ponds. The current design has one in the protected area and two in the balance of site at opposite ends to facilitate grading flow. 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.

Mine water pumped from the underground sumps will be piped to a mine dewatering settling pond. The mine 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), possibly particular metallic elements (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 mine 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).

Excavated Rock Management Area

An Excavated Rock Management Area (ERMA) is a separate facility that will receive the excavated rock from underground construction. The ERMA location will be within a 5 km distance of the repository shafts, and will be selected to avoid streams and wetlands. The ERMA will occupy an area of approximately 25 hectares (~500 m x 500 m) with a reference rock pile height of 15 m, and have a capacity of approximately 2.5 million cubic metres of rock required for all underground excavation over the life-cycle of the facility. The ERMA will be fenced during construction and operations.

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 stormwater that falls on and percolates through the rock pile becomes contaminated. In particular, whether this water become acidic or has a high concentration of metals or salt. This is determined in advance through standard laboratory leachate tests. Leachate tests characterize soluble parts of the rock and are used to predict migration and associated risk; for example, these types of tests can determine if the excavated rock is potentially acid generating (PAG).

Preliminary testing of Ignace 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.

The preliminary testing provides confidence that PAG conditions will not be a concern at the Revell Site; nonetheless, the NWMO is still advancing ERMA designs that take this scenario into consideration. 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 developing the ERMA with a composite or multiple-layer 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 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 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.

7.4.1 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 7.11 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 7.11.

Based on information to date, there is high confidence that the surface area and infrastructure can support the construction, operations, and closure of the repository.

7.4.2 Overburden

Geological mapping in the Revell batholith area indicates good bedrock exposure with generally low levels of overburden (soil cover) 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.

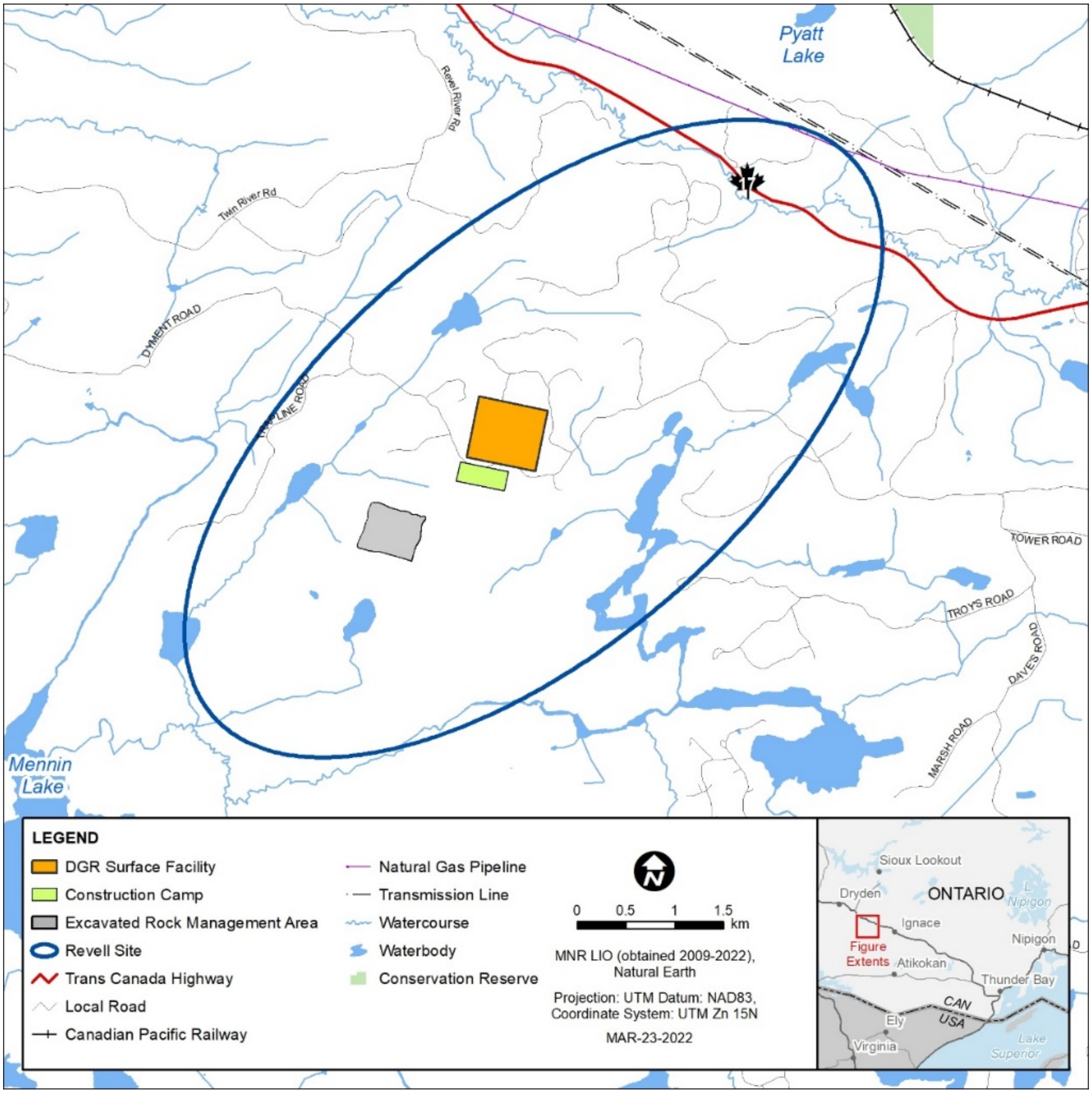

Figure 7.11: Conceptual locations for DGR surface facilities and excavated rock management area at the Revell Site

7.4.3 Host Rock Strength and Bedrock Stresses

As noted in Section 3.6, while there are no direct bedrock stress measurements at this time, potential borehole breakout data suggests that the orientations of the maximum horizontal stresses follow the general trend in the Canadian Shield. 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 3.6, 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.

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, 2021c) and *Preliminary Transportation Plan* (NWMO, 2021d).

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 steel body and lids, which are attached with several large lid bolts. The lid and bolts are 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.

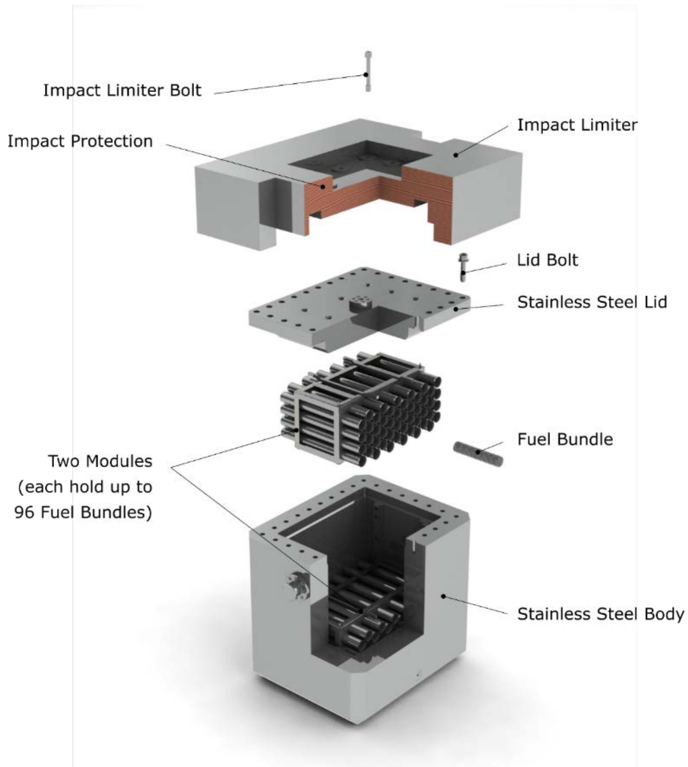

Figure 8.1: Illustration of Used Fuel Transportation Package (UFTP). A stainless-steel package with walls nearly 30 centimetres thick.

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 is a package for transporting cylinder fuel baskets used at 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, 2021c and 2021d) 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 using a half-scale model as shown in Figure 8.2. The package passed all testing and is currently certified for use.

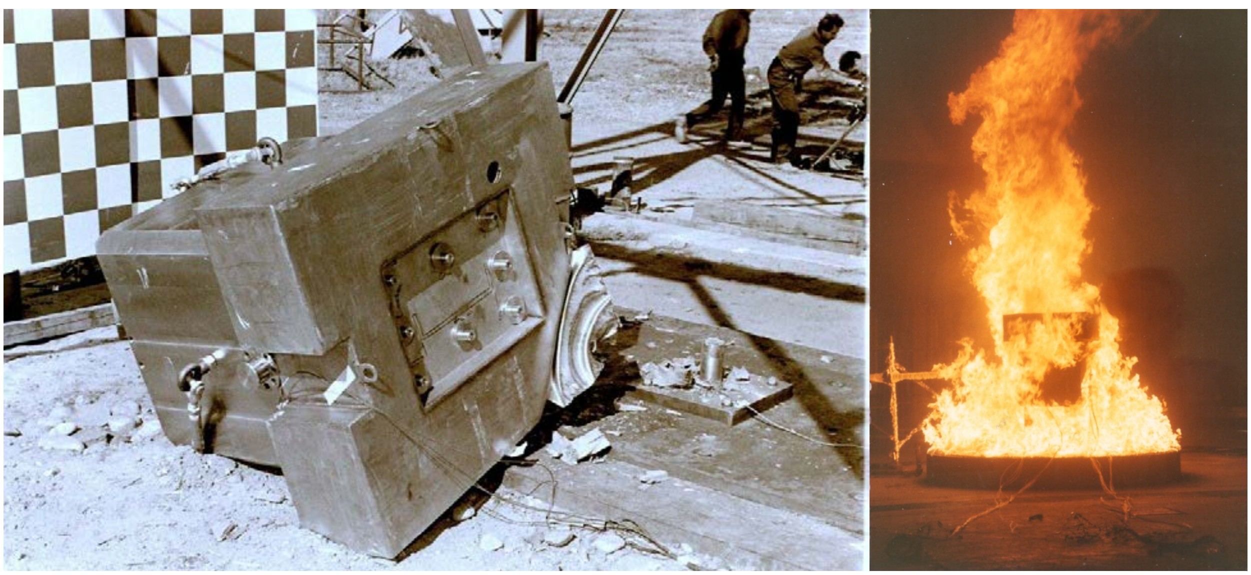

Figure 8.2: Half-Scale Used Fuel Transportation Package: (Left) after drop test; and (Right) during fire testing

Figure 8.3: Photos from "Operation Smash Hit". A used fuel transportation package in direct collision with train traveling at 160 km/h with no release of contents. (Clockwise) Depicts train just before collision, after collision, and dented but intact package among wreckage.

Several countries have conducted additional testing to demonstrate the robustness of used fuel transportation packages. 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 nor release it contents. 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 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 logistically advantageous. A road/rail combination system is possible depending on the interim storage site. Some interim storages sites will require an intermodal facility to transfer transportation packages from a tractor-trailer to train; additionally, some 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.

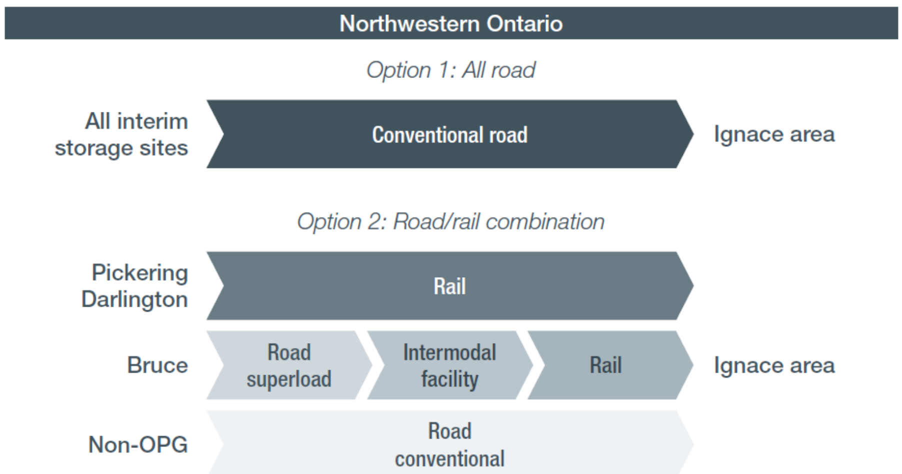

Figure 8.4: Transportation systems under consideration for the Revell Site

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 7.11).

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). The NWMO has confirmed the technical feasibility of both of these connections.

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. The intermodal facility would transfer the used fuel transportation packages to/from rail to road transportation modes (e.g., train to/from trucks). A conceptual intermodal facility is shown in Figure 8.5.

The NWMO has confirmed the technical feasibility of both of these transportation systems; 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, avoids the need for intermodal facilities and superload shipments.

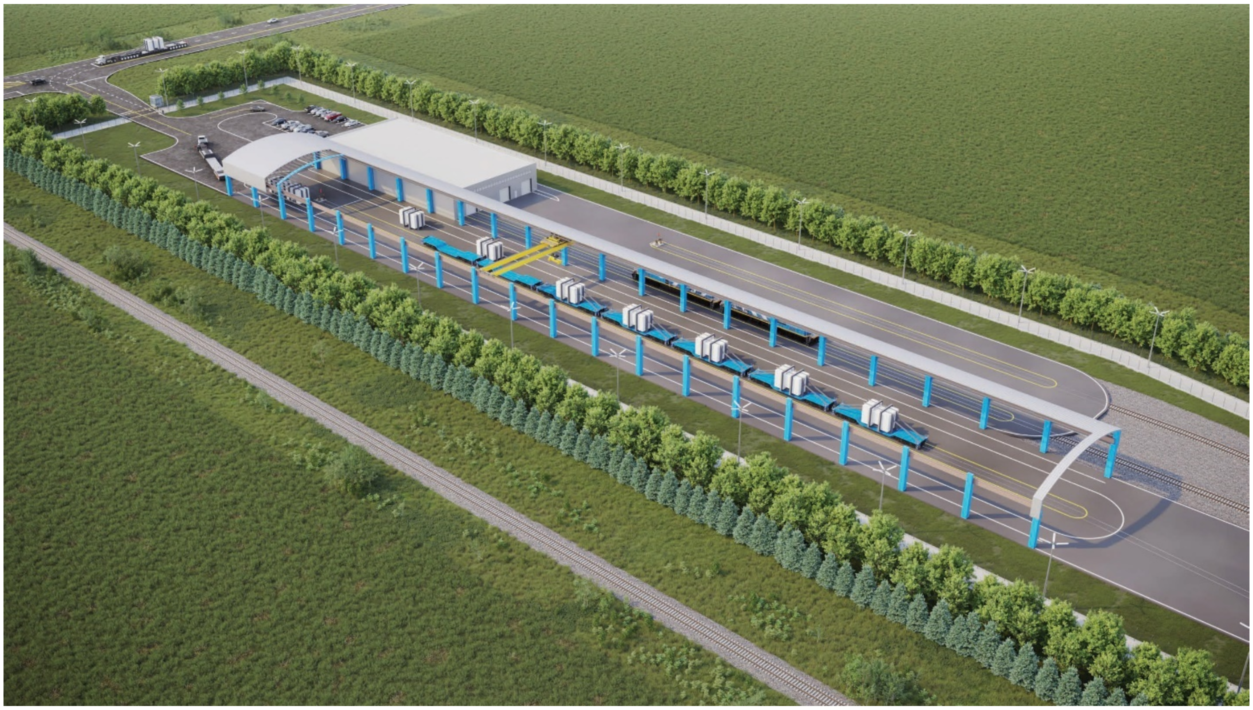

Figure 8.5: Conceptual Used Fuel Transportation System Intermodal Facility to transfer packages from rail to road modes.

8.2 Safety, 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 security and emergency response planning and protocols from being implemented effectively. Similar plans have been successfully applied nationally and internationally on used fuel shipments for over 50 years. As a result, there is high confidence that a safe and secure transportation system can be designed and operated.

8.2.1 Security

A license from the CNSC is required to transport used nuclear fuel. As part of the license 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.

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 assists 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.

9. NATURAL ANALOGUES

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.

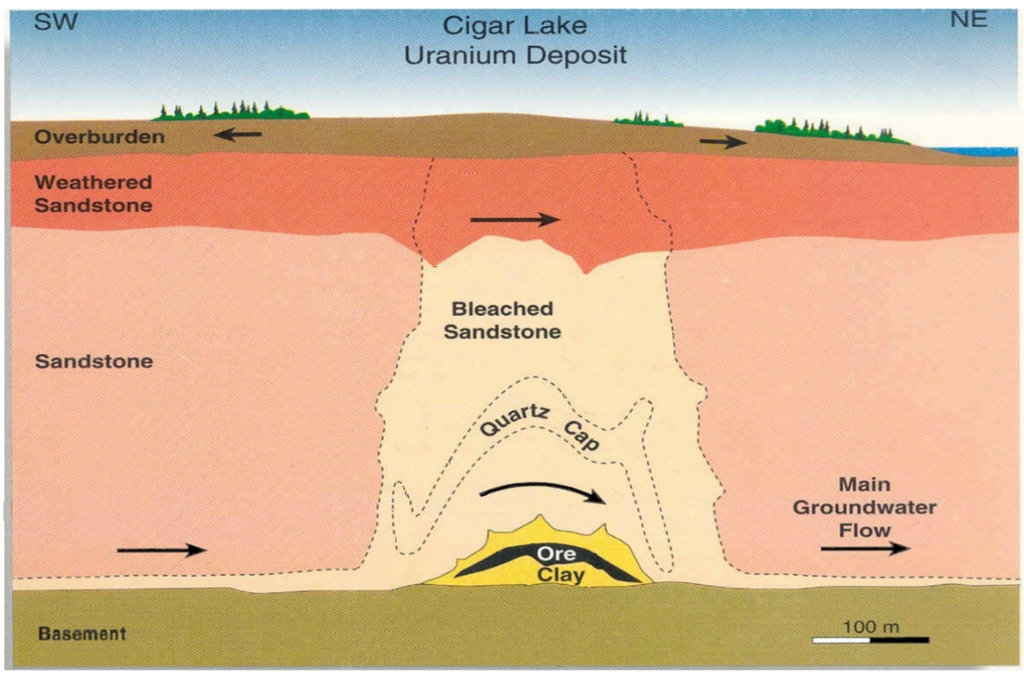

Figure 9.1: Cross-section of the Cigar Lake uranium ore body in Saskatchewan (adapted from Cramer and Smellie 1994). The uranium ore, surrounded by a clay layer at 430 m depth, has remained isolated from the surface environment for over 1.3 billion years.

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

A safety assessment is performed to demonstrate that the deep geological repository will meet regulatory safety criteria, taking uncertainties into account. That is, it will show that the system is robust. The safety assessment does this in part through demonstrating that under many scenarios, both likely and unlikely, the potential maximum dose to a future family living on or near the repository, using local well water and growing their own food, would not exceed the regulatory limit.

The safety assessment is a systematic quantitative analysis of the performance of the repository and comparison of this performance against criteria. The basis for the assessment is described in Canadian regulatory documents (notably REGDOC-2.11.1, CNSC 2021a,b), 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 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. The first two 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 (CEAA 1998). The most recent Canadian study for a crystalline rock site was called the Sixth Case Study (NWMO 2017).

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

Although the geological environment and details of the repository concept varied from study to study, these studies found that geological disposal of used nuclear fuel in a suitable rock and site 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.

For the assessment of the Revell Site, the process starts with the understanding of the site developed through the site characterization and environmental baseline programs, and the development of the engineering design for the site. This information is used in the safety assessment. As more information becomes available, and as part of the licencing process, the safety assessment is progressively iterated to provide a more detailed assessment.

At the present time, the initial NWMO assessment for the Revell Site has assumed rock properties based largely on properties observed in other Canadian Shield settings that could be considered appropriate for hosting a repository. These assumptions will be revised as more site-specific information is collected.

The safety assessment evaluates the performance of the repository before and after its closure for various scenarios. During the pre-closure period, these include normal operations and accident scenarios. During the post-closure period, these scenarios consider the likely or expected future behavior of the site, as well as unlikely or what-if scenarios. In particular, for understanding the potential impacts, the post-closure safety assessment estimates the consequences of container failure, considering anywhere from a small number to all containers failing. The potential peak dose impacts are assessed assuming a future family living at or near the repository. (Potential impacts on people living further away would be less.)

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, and for humans, radiation dose is reported here in units of millisieverts (mSv).

People are constantly exposed to nuclear radiation from naturally occurring sources 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). This natural background radiation varies by location; for example it is about 1.5 mSv in Toronto and about 4.0 mSv in Winnipeg. Around Ignace, the natural background radiation dose is estimated as about 2.0 mSv per year (Arcadis 2022).

In Canada, the nuclear regulator CNSC has set the dose limits for members of the public at 1 mSv per year above background, and for nuclear energy workers at 20 mSv per year (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.

The initial safety assessment makes the unlikely assumption that multiple containers have failed and that a future family is living at or near the site where they would be at highest exposure. This analysis indicates that the potential peak dose rate would be below regulatory limit and the natural background dose rate. There would be no health effects to this assumed future family.

This assessment will be revised using more site specific information.

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 two are in licencing. 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). www.cnl.ca/environmental-stewardship/near-surface-disposal-facility-nsdf/

- 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; cast iron structure; surrounded by bentonite clay	Olkiluoto reactor site on southwest coast	Construction in progress. Operating licence application in 2021.
Sweden	Used fuel	Crystalline rock (granite)	470 m	Copper shell; cast iron structure; surrounded by bentonite clay	Forsmark reactor site on east coast	Construction licence approval in 2022 (method and site)
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	Preliminary construction licence application in 2019.
Switzerland	Vitrified HLW and used fuel	Clay rock	400 – 1000 m	Steel canister (copper coating under evaluation)	Siting process under way in three siting regions in northern Switzerland	Site selection in late 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). In particular, environmental monitoring is standard practice at all nuclear facilities including uranium mines.

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

At the Revell Site, instrumentation to monitor pressures is in place for three boreholes, with a fourth instrument to be installed in 2022. 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.

<u>Site Preparation and Construction Phase</u>

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 emplacement room. Monitoring equipment would be installed as part of these tests located within the central services area.

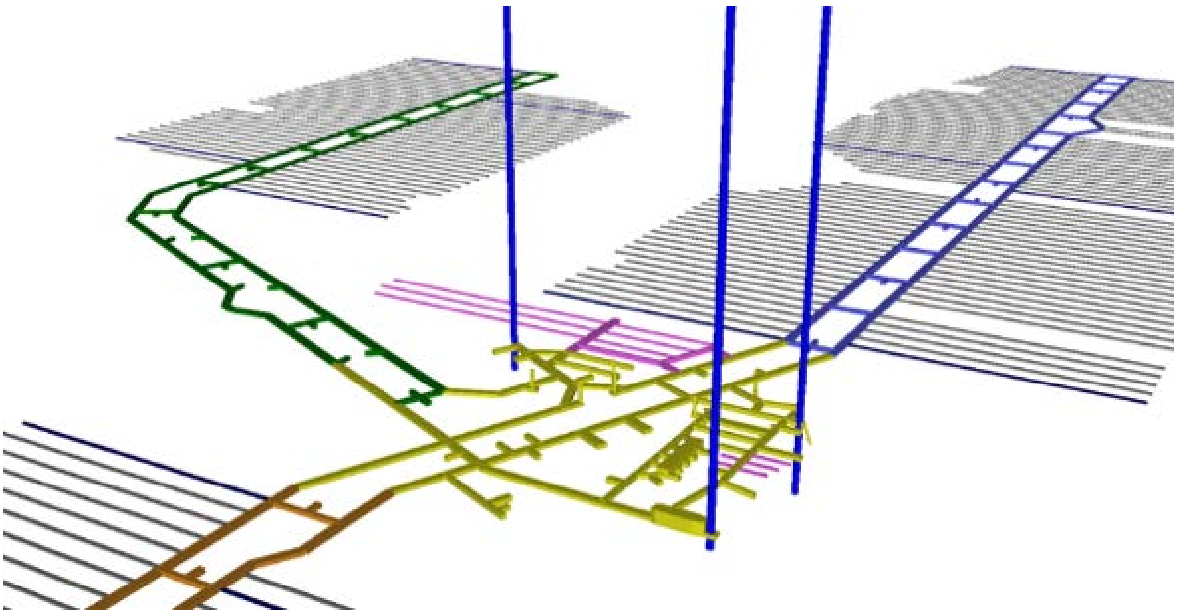

Figure 12.1: Illustration of centralized service area of repository showing the underground demonstration areas (highlighted in purple). (For illustration purposes only; does not reflect site specific layout for Revell Site).

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 emplacement room tests.

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

The third category of monitoring covers specialty tests that may occur across the repository and check aspects of performance of the as-emplaced 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. For example, large scale experiments to date have embedded sensors within buffer elements, and have often observed that the power or signal cables can affect the test as they penetrate through the otherwise self-sealing clay buffer. Also, many of these instruments have a lifetime measured in years under in-situ conditions, which is short relative to the potential time frame of interest. Together, this puts an emphasis on monitoring that is remote, such that the instruments can be maintained if necessary and such that they do not interfere with the controlled conditions in the engineered barriers.

These constraints generally limit the testing to that conducted through boreholes around an emplacement room, with enough standoff distance to minimize risk of interference with the rooms, and to remote sensors such as acoustic emission monitoring.

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 microseismics 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.

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. In part, there would be land use controls imposed. And key information files would be preserved widely and in various formats. It is anticipated that some type of marker would be provided at the site itself.

13. REGULATORY FRAMEWORK

The NWMO facility is defined as a Class IB nuclear facility under the federal *Nuclear Safety and Control Act* and regulations.

Canada has a well-developed regulatory framework for evaluation of safety of nuclear facilities. This framework is consistent with international best practice (e.g., IAEA 2011a, 2011b), and requires the proponent to complete a series of licensing decision steps, with progressively more information.

The first formal step is 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 licencing).

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 (see, for example, Figure 14.1).

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. This will be further studied as part of the detailed site characterization, if the Revell Site is selected as the preferred site. During repository construction, further information will be obtained by characterisation of tunnel walls, drilling of pilot holes, and other techniques to confirm the nature of the geology.

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, and they can also be impermeable. Fractures can also be a heterogeneous combination of both permeable and impermeable regions. Fracture distribution and intensity will also influence repository design. However, many fractures were formed long ago, and have been altered and infilled by minerals, such that they are not simple permeable pathways. 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 multiple deep boreholes was the lack of opportunity to collect groundwater samples. To date, the rock encountered has been tight (i.e., only a few intervals have been identified with 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. Together, the groundwater and porewater chemistry are important datasets used to develop an understanding of the relative ages of fluids within the shallow to deep groundwater systems, and to allow assessments to be made of potential interactions with engineered barrier materials should the site be selected to host a repository.

These uncertainties noted above are being addressed through several approaches. Additional studies are planned, including more fieldwork and drilling of additional boreholes as part of the detailed site characterization program should the Revell Site be selected. Also, the wide range of measurements that have been done 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 and long-term pressure monitoring of boreholes are continually adding to a regional database of geoscientific information. Formally, 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.

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.

In addition to the ongoing geological and environmental site characterization work, there is work underway to improve the engineered barriers and the design, and to conduct safety assessments.

A site-specific engineering design is presently being developed, as well as continued optimization of the fuel handling and emplacement systems. In 2022, for example, full-scale non-nuclear trials at NWMO's test facility are planned to demonstrate prototype emplacement equipment. Important areas of work include the underground layout and the specific repository depth.

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.

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, including in particular Finland and Sweden which have approved sites for their planned deep geological repositories.

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. Neither of the two sites have yet been identified as the preferred site.

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.

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 management 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. And even after construction and then operations begins, 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.

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

Arcadis. 2022. Ambient Radioactivity – The Ignace Area (draft). Prepared by Arcadis Canada Inc. for Nuclear Waste Management Organization. Richmond Hill, Canada.

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

Atomic Energy of Canada Limited (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.

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.

Canadian Nuclear Laboratories (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.

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

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

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

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

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

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

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

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.

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.

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). Mississauga, Canada.
Available at: https://www.nwmo.ca/~/media/Site/Reports/2015/11/12/06/37/Ignace---Full-Report_med.ashx?la=e

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.
Available at:
https://www.nwmo.ca/~/media/Site/Reports/2015/11/20/07/18/2214_apmrep061440011_ignace_geoscience_mainreport_we.ashx?la=en

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.
Available at: https://www.nwmo.ca/~/media/Site/Reports/2018/03/02/16/01/1532407-7000-Ignace-Ph2-Findings-27Nov2017.ashx?la=en

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 (NWMO). NWMO Report Number: APM-REP-01332-0225. 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.

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. Finalreport. SKB TR-19-07, Svensk Kärnbränslehantering AB.

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

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

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

Ministry of the Environment (MOE). 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.

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

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

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

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

Nuclear Waste Management Organization (NWMO). 2021a. Nuclear fuel waste projections in Canada – 2021 Update. Nuclear Waste Management Organization Report NWMO-TR-2021-17. Toronto, Canada.

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

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

Nuclear Waste Management Organization (NWMO). 2021d. Preliminary Transportation Plan. Nuclear Waste Management Organization. Toronto, Canada. https://www.nwmo.ca/~/media/Site/Files/PDFs/2021/12/13/19/30/Preliminary-transportation-plan--December-2021--EN.ashx.

Organisation for Economic Co-operation and Development (OECD). 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.

Peltier, W.R. 2011. Long-Term Climate Change. Nuclear Waste Management Organization Report NWMO DGR-TR-2011-14 R000. Toronto, Canada.

Pescatore C, Hotzel S, Berckmans A, Claudel A, Dumont J-N, Tunbrant S, Wisbey S, Van Luik A, Schroeder J. 2019. Preservation of Records, Knowledge and Memory (RK and M) 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 2007-06. Olkiluoto, Finland.

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

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

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.

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

Sander Geophysics Limited (SGL). 2020. 3D Geophysical Forward and Inversion Modelling of the Revell Batholith and Surrounding Greenstone Belt. (No. APM-REP-01332-0270). Nuclear Waste Management Organization. Toronto, Canada.

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

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

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.

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

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

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

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 coipper containers in permeable plutonic rock, Volume I: Summary. Atomic Energy of Canada Limited report AECL-11494-1, COG-95-552-1. Pinawa, Canada.