Confidence in Safety - South Bruce Site - 2023 Update

NWMO-TR-2023-08 **December 2023**

Nuclear Waste Management Organization

NUCLEAR WASTE MANAGEMENT ORGANIZATION
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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 consistent with plans in other countries with nuclear power programs, including Finland, Sweden, France and Switzerland, which have sites for their deep geological repositories for nuclear fuel waste.

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

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

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

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

The NWMO’s assessment of the suitability of the South Bruce Site is based on site-specific results acquired to date, as well as regional information, the intrinsic characteristics of the repository multiple barrier approach, and from similar projects in other countries. In particular, information gathered at the Bruce nuclear site highlighted the favourable containment and isolation properties of the near-horizontally layered, Ordovician-aged shales and limestones, including the limestone of the Cobourg Formation. Borehole drilling confirms that these same Ordovician sedimentary rocks extend beneath the South Bruce Site.

The NWMO is confident that a repository located in the Cobourg Formation, located about 650 m below the surface at the South Bruce Site, will allow for safe repository construction and operation, and that the used nuclear fuel will remain isolated from the surface and near-surface environment for sufficiently long times.

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

1. The favourable characteristics of the geology at the South Bruce Site.

    - A 400-m thick succession of low-permeability Ordovician-aged sedimentary rocks (444-460 million years old), present beneath the South Bruce site, including the approximately 40 m thick Cobourg Formation at a depth of about 650 m, bounded above by more than 200 m of shale and below by more than 150 m of limestone and argillaceous (clay-bearing) limestone. This natural barrier system has the depth, breadth and volume to isolate the repository from surface disturbances and changes caused by human activities and natural events.

    - No active geological features (e.g., faults) or unfavourable heterogeneities have been identified in the Cobourg Formation or bounding Ordovician-aged sedimentary rocks at the South Bruce Site to date. This is a favorable indication of the long-term stability of the site and of its ability to contain the used fuel.

    - Based on results from the first two boreholes, no permeable Cambrian sandstone is present below the South Bruce Site. No groundwater samples could be collected below 325 m depth and very low groundwater flow is expected at repository depth. These favourable hydrogeological indicators support the long-term containment and isolation capability of the site.

    - The composition of porewaters extracted from core samples indicates highly saline conditions within the Ordovician-aged bedrock. No geochemical evidence has been found for the infiltration of glacial or recent meteoric recharge water into this host rock.

    - The site-specific properties of the Cobourg Formation indicate that this rock will be capable of removing the heat generated by radioactive decay of the used fuel and withstanding both natural and thermal stresses induced by the repository.

    - While no direct in situ stress information is yet available for the South Bruce Site, it is expected based on regional information and results from numerical simulations that bedrock stress conditions encountered during construction will be safely manageable.

2. The stability of the geosphere.

    - The Cobourg Formation, and the Ordovician-aged sedimentary rocks above and below it at the South Bruce Site, are about 444-460 million years old.

    - The South Bruce Site is located in a stable, seismically quiet setting overlying Precambrian rocks of the Canadian Shield at the heart of the North American continent, far from tectonic plate boundaries and is therefore not prone to large earthquakes and recent volcanic activity.

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

- The highly saline fluids (including water and gases) within the small pores in the Ordovician-aged rocks are distinct from the low salinity fluids in the shallow bedrock layers. Analogous results from the Bruce nuclear site have been used as evidence that such fluids have been there for hundreds of millions of years and are isolated from the surface environment.

- Borehole testing has identified underpressured and low permeability conditions in the Cobourg and bounding Ordovician formations beneath the site. Analogous results from the Bruce nuclear site have been used as evidence that the Ordovician formations beneath the South Bruce site have been isolated from the normal pressures of the near-surface environment for millions, if not hundreds of millions, of years.

- Paleoclimate modelling provides estimates of the impact of future glaciations, including maximum ice and permafrost thickness. Model results align with site-specific observations and indicate that the containment and isolation functions of the geosphere will be maintained at the repository depth during and after future glacial events.

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

   - Other than surficial aggregate resources, no known economically exploitable mineral resources, hydrocarbon resources or salt resources have been previously identified at the South Bruce Site. No economically significant concentrations of these resources were identified in the two boreholes at the site.

   - The water below about 200 m at the site is increasingly saline, consistent with the understanding that water wells in the Municipality of South Bruce obtain potable water from overburden or bedrock sources between 3 m and 163 m below ground surface.

4. The site is amenable to geological characterization.

   - Results from borehole drilling confirm the low fracture frequency, homogeneous character, and overall predictable nature of the Ordovician bedrock at the site.

   - Results from a three dimensional (3D) seismic survey confirm that the Cobourg and bounding Ordovician formations are laterally continuous and have uniform thickness beneath the site.

   - The hydrogeological characteristics of low permeability, evidence of underpressures, and the highly saline porewaters within the Cobourg and bounding Ordovician formations are consistent with expected conditions based on the Bruce nuclear site analogue.

5. The robustness of the multiple barrier system.

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

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

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

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

    - Results from laboratory geomechanical and thermal testing of the Ordovician-aged rock core samples compare favourably with other sedimentary formations considered internationally for long-term radioactive waste management purposes.

    - Experience in southern Ontario with underground excavations in the Ordovician limestones, including the Cobourg Formation, indicates that they are naturally dry and stable, and can be managed with standard engineering practices.

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

    - The South Bruce Site has suitable underground area for placement of the projected used fuel from Canada's existing nuclear fleet. The NWMO-owned and optioned land has some expansion capacity.

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

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

    - The South Bruce Site is approximately 10 km south of Ontario Highway 9. The Goderich-Exeter Railway rail line is approximately 75 km to the south, depending on route and access point. Electrical transmission and natural gas distribution are available in the region.

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

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

    - The South Bruce site is within 15 km of an existing highway supported by local road network. There is no rail infrastructure nearby, so direct rail transport is not feasible. An all road and a road/rail combination transportation system are technically feasible for the site.

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

- All countries that have decided on the long-term management of their used fuel have plans for a deep geological repository for this purpose.
- The Canadian regulatory framework has defined steps and expectations for licensing a repository. It is consistent with international best practice.
- A preliminary site-based safety assessment indicates that there would be no impacts on human health during normal operations or post-closure. The results are similar to safety assessment studies to date for other sedimentary rock sites, which have indicated that a repository in these rock types can perform well.
- Baseline monitoring is in-place or underway, including in deep boreholes and shallow groundwater wells, surface water bodies, seismicity and meteorological conditions, as well as biodiversity studies.
- The site will be monitored for decades during site characterization, preparation, construction and operation, before a decision is made to close the repository. This monitoring will support the repository construction and operations, as well as confirm that the repository is not causing harm to people or the environment.

Overall, based on the assessment results to date, the NWMO is confident that a deep geological repository can be constructed at the South Bruce 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 South Bruce Site to safely contain and isolate used nuclear fuel, and more about continuing to develop and document a thorough quantitative understanding of the site.

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

- One area that will require additional effort in the future is the high salinity of the Ordovician-aged bedrock. While this is a favorable indicator for the stability of the geology, its potential effects on the engineered systems will require additional analysis.
- There is a reef structure in the Guelph Formation 300-m above the proposed repository depth, and a sediment-filled valley along the west side of the site. While the reef, and the buried valley, do not directly impact the containment and isolation properties of the underlying Ordovician-aged formations, their geometry and character will continue to be investigated to support repository design and to accurately model surface and shallow groundwater movement.

- While the 3D seismic investigation has not identified any steeply dipping faults beneath the site, the presence or absence of such structures will continue to be investigated by inclined drilling. Furthermore, recognizing that the South Bruce Site is located in a region of low seismic hazard, microseismic monitoring is on-going to determine if any active faults are present in the region around the site.

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

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

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

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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

PAG – Potentially Acid Generating

RQD – Rock Quality Designation

UDF – Underground Demonstration Facility

UFC – Used Fuel Container

UFPP – Used Fuel Packaging Plant

UFTP – Used Fuel Transportation Package

1. INTRODUCTION

1.1 Background

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

The Government of Canada selected the deep geological 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 http://www.nwmo.ca/Site-selection.

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

This report focuses on the site in the Saugeen Ojibway Nation (SON) – South Bruce area. This South Bruce Site is located approximately 5 km northwest of Teeswater in the Municipality of South Bruce. It is about 30 km inland from Lake Huron (Figure 1.1 and Figure 1.2)

Figure 1.1: Typical landscape at the South Bruce Site in southern Ontario.

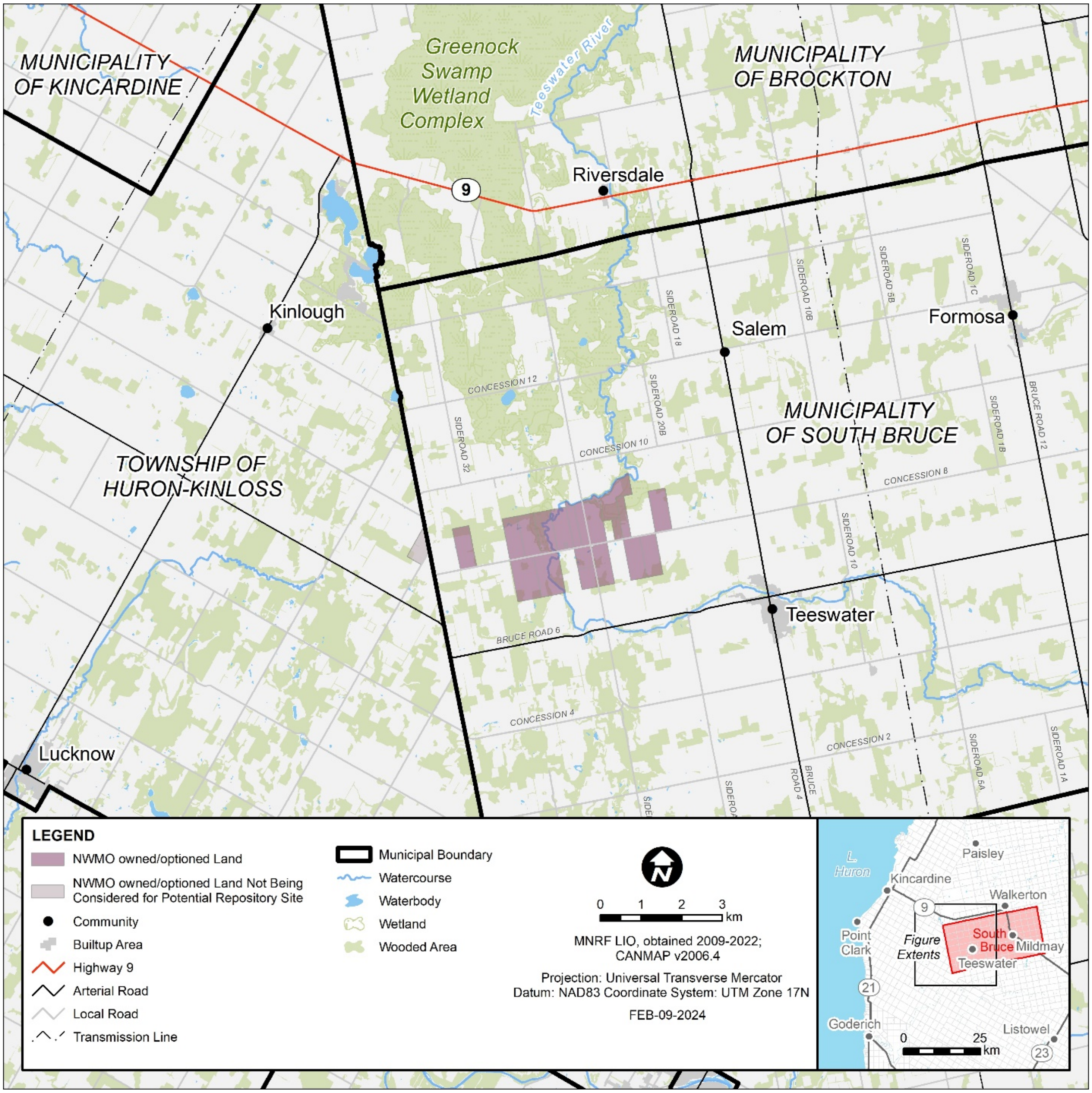


Figure 1.2: General location of the South Bruce Site in southern Ontario. Inset map shows main figure location in relation to the Municipality of South Bruce. The repository surface facilities and underground rooms would be located on or under NWMO owned land. Over 1,500 acres have been secured by the NWMO.

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 geological environment, surrounded by multiple barriers. This strategy is referred to here as a **deep geological repository** (also DGR or repository).

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

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

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

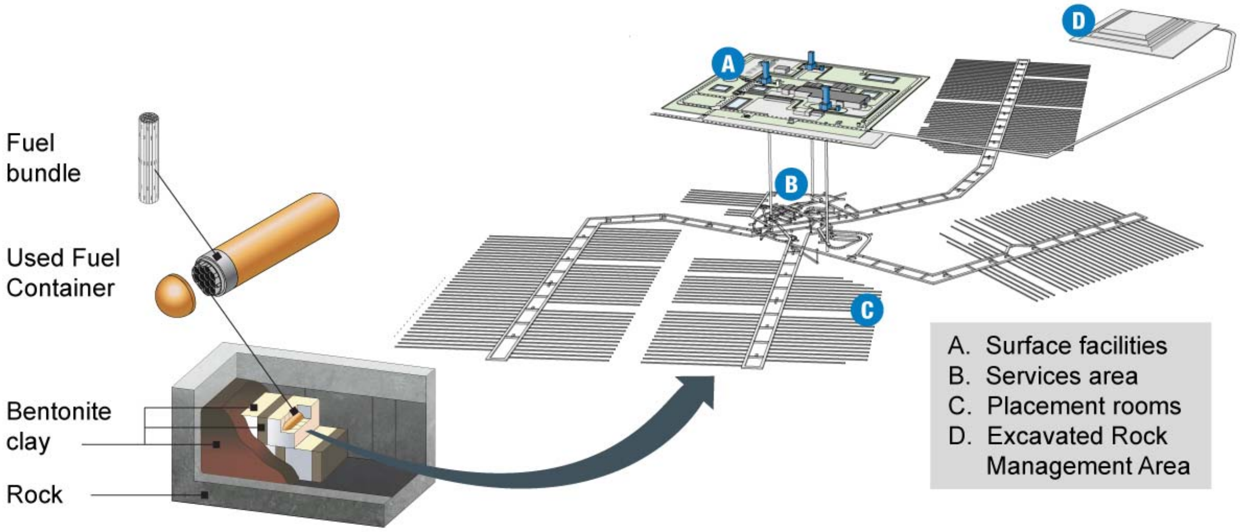


Figure 1.3: Deep Geological Repository concept

1.3 Saugeen Ojibway Nation (SON) - South Bruce Area

The South Bruce Site is within the SON-South Bruce area in southern Ontario (Figure 1.1 and Figure 1.2).

The SON-South Bruce area is located in the western St. Lawrence Lowland, a low relief, gently undulating land surface that occupies much of southwestern Ontario and is covered with glacial sediments. The land surface ranges from a maximum of 249 metres above sea level in the southeast corner of the Municipality of South Bruce to a minimum of 176 metres along the shore of Lake Huron in the Township of Huron-Kinloss. The land surface shows a general slope down towards Lake Huron from southeast to northwest. A flat low-lying area, associated with the Greenock Swamp wetland, is located north of the site downstream along the Teeswater river.

The SON-South Bruce area is a predominantly agricultural landscape located at the transition of Ontario forest zones. It lies within the Deciduous Forest Region where woodlands consist primarily of American beech and sugar maple, on the northern limit of the Carolinian Forest. In areas where agriculture dominates, terrestrial features and areas are generally associated with valley lands along watercourses and within wetlands.

The most prominent drainage feature in the area is the Teeswater River, which flows from east to west in the Municipality of South Bruce, bending to flow northward and discharging into the Saugeen River at Paisley.

Shallow bedrock is the most important source of drinking water in the area, and is the primary source for municipal water supplies. Shallow bedrock aquifers within the area comprise the upper few metres to over 100 m of bedrock formations. Water quantity and quality within the shallow bedrock aquifer can vary dramatically across the area as a consequence of the different chemical and physical characteristics of the individual bedrock formations.

Further information on the environment is provided in the NWMO Phase 1 Assessment report (NWMO 2014). This information is presently being updated as part of the NWMO site baseline studies and environmental baseline monitoring program.

1.4 Purpose of Report

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

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

This report presents the safety basis and the associated uncertainties as they stand as of mid-2023. Our understanding of the site is based on existing regional information plus site-specific data. The regional information notably includes results from a detailed geological site characterization program at the Bruce nuclear site about 40 km distant, and observations from oil and gas wells across southern Ontario. Site-specific observations are from drilling, coring and testing two deep boreholes at the site, and preliminary results from a 3D seismic survey as well as installation and monitoring of a network of shallow wells.

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

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

This report is part of a 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 Laboratory site in Ontario (NWMO 2022). Ontario Power Generation (OPG) is now planning to build a GEH BWRX-300 Boiling Water Reactor (BWR) at its Darlington site with a licence to construct application submitted.

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

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

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

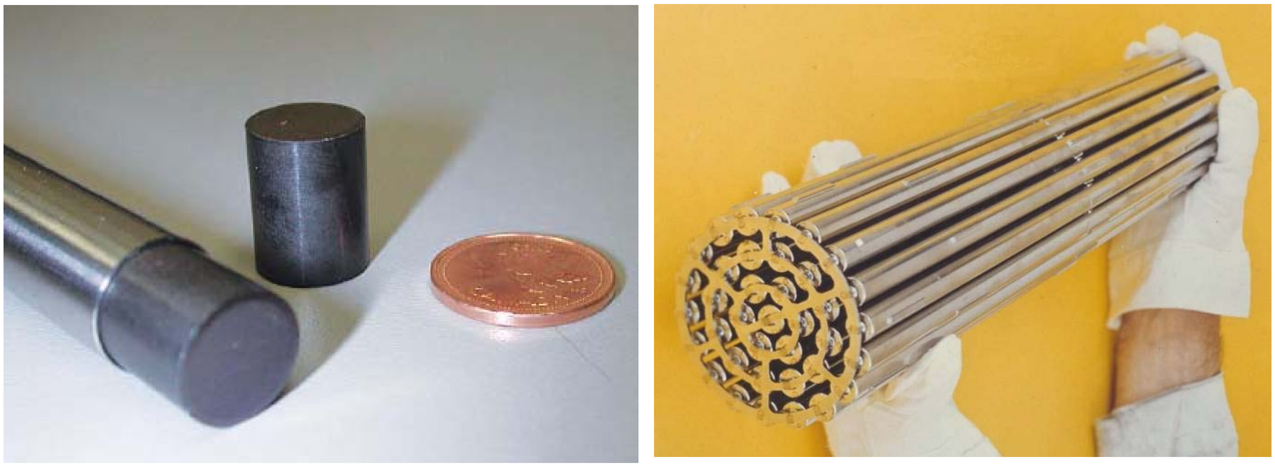


Figure 2.1: (Left) Ceramic UO_2 fuel pellets before irradiation, and pellets fitting inside Zirconium alloy cladding. (Right) Typical CANDU fuel bundle before irradiation

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

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

Many of the new atoms formed are unstable, i.e., they are **radioactive** atoms or **"radionuclides"**. In this process, the atom spontaneously releases energy, and changes into a different type of atom, a process called **radioactive decay** or **radioactivity**. This decay energy is released as various types of **radiation**, including alpha, beta and gamma radiation.

Eventually, all radioactive atoms decay into stable atoms and do not release further radiation. This radioactive decay is a natural process. It can take anywhere from fractions of a second to occur, to longer than one million years, depending on the particular type of atom. Radioactivity is measured in **Becquerels (Bq)** where 1 Bq is one atom decay per second. Uranium is an example of a naturally occurring radioactive atom.

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

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

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

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

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

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

*Includes impurities naturally present in fuel

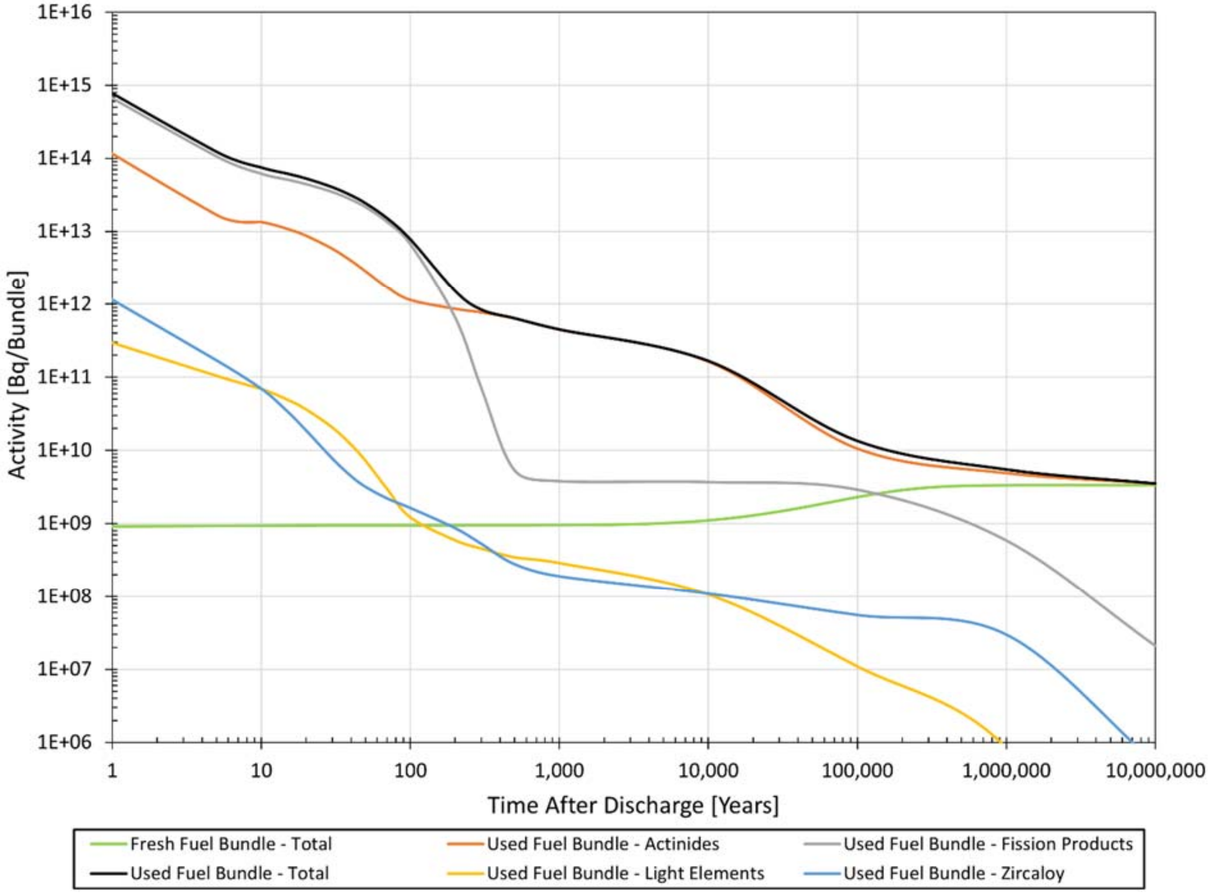


Figure 2.2: Radioactivity of used CANDU fuel decreases with time (fuel burnup of 220 MWh/kgU)

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

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

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

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

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

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

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

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

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

3. LONG-TERM GEOLOGICAL CONTAINMENT AND ISOLATION

The repository must contain and isolate the used nuclear fuel. To ensure this, the geoscientific conditions (properties and processes) of the South Bruce 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 South Bruce 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 regional information, and by site characterization studies in the South Bruce area that were initiated in 2012 and are still underway. To date, these include:

- 2012 - Initial Screening desktop study (AECOM 2012)

- 2012-2014 - Phase I Desktop preliminary assessment (Geofirma 2014)

- 2020-2023 - Initial Phase 2 preliminary assessment field studies, including borehole drilling, coring and testing, 3D seismic survey, on-going microseismic monitoring and shallow groundwater well installation and monitoring.

Phase I studies were based mostly on available information from historic oil and gas exploration, 2D seismic data, airborne geophysical surveys, and the results of a detailed characterization of the sedimentary rocks beneath the Bruce nuclear site (Intera 2011, NWMO 2011). This site characterization work at the Bruce nuclear site was completed as part of OPG's proposed Deep Geological Repository for Low & Intermediate Level radioactive waste.

Studies carried out after Phase I Preliminary Assessment provide additional insight into the geology at the South Bruce Site, including an updated three-dimensional (3D) geological model of the stratigraphy of the entire region of southern Ontario (Carter et al. 2021), and site-specific studies completed by the NWMO to date, including:

- Drilling of two deep boreholes through the entire sedimentary sequence and into the Precambrian rocks beneath the site;
- Installation of a long-term monitoring system in one deep borehole;
- Completion of a 3D seismic survey;
- Installation of a network of shallow groundwater monitoring wells; and
- Installation of a network of microseismic stations.

In addition, knowledge about the expected behaviour of sedimentary rocks, both specific to the southern Ontario geological setting and from around the world, is used by the NWMO to develop a general understanding of the expected nature of the South Bruce Site. This includes information from Canadian academic, geological survey, and mining industry sources, as well as from international academic and nuclear waste management organizations. In particular, information gathered during a multi-year characterization project at the Bruce nuclear site highlighted the favourable containment and isolation properties of the near-horizontally layered Ordovician-aged shales and limestones, including the Cobourg Formation limestone (NWMO 2011). The Phase I Desktop Preliminary Assessment (Geofirma 2014) provided an initial understanding of the geology at the South Bruce Site and identified the **Cobourg Formation** (named as such because it reaches the surface to outcrop near Cobourg, Ontario) as a potentially suitable host rock formation for siting a deep geological repository in South Bruce.

Together with the site-specific information gathered to date, this natural analogue information provides a strong basis for demonstrating the long-term geological containment and isolation potential of the Ordovician bedrock, and in particular the Cobourg Formation, beneath the South Bruce Site.

3.1 Geology of the South Bruce Site

The South Bruce Site is located on the eastern flank of the **Michigan Basin**. This basin consists of laterally extensive sedimentary rock formations deposited between approximately 540 and 300 million years ago on the ancient continental margin of eastern North America. As shown in Figure 3.1, the Michigan Basin is centered in Michigan and extends across southern Ontario, where it eventually thins out above the underlying Precambrian (older than 540 million years) basement granitic rock of the Canadian Shield.

The Michigan Basin is about 4800 m deep at its center (Figure 3.1) and about 900 m deep at the South Bruce Site. It was formed as a series of sedimentary layers. A cross-sectional geological model for southern Ontario, including the South Bruce Site, is illustrated in Figure 3.2 showing the major layers. These layers are labelled first according to when the sediments were deposited on the underlying Precambrian basement rock. Cambrian: about 485-540 million years ago, Ordovician: about 444-485 million years ago, Silurian: about 419-444 million years ago, Devonian: about 360-419 million years ago. The bedrock is overlain with Quaternary sediments, which are unconsolidated sands, clays and soils, deposited within the past 2.6 million years.

Figure 3.3 provides a more detailed breakdown of the typical rock units that underlie southern Ontario, including the South Bruce Site (middle column in Figure 3.3 below), based on the recently updated 3D stratigraphic model (Carter et al. 2021).

The Cobourg Formation is a laterally extensive layer or unit of rock, extending under much of the Michigan Basin, including beneath the entire South Bruce Site. The Cobourg Formation limestone is known to be a strong, low-permeability rock (NWMO 2011). It lies beneath a thick layer of low-permeability shales of the Blue Mountain, Georgian Bay, and Queenston formations (see Figures 3.2 and 3.3). The Cobourg Formation is also underlain by limestones of the Kirkfield and Sherman Fall Formations. The Cobourg Formation, together with these bounding Ordovician-aged layers above and below it, is the primary natural barrier for a repository beneath the South Bruce Site.

The NWMO initiated the drilling and testing of two deep boreholes (SB_BH01 and SB_BH02) at the site in 2021 and completed the drilling and testing in 2022. Results from the drilling of these boreholes at the South Bruce Site confirmed, for the Cobourg Formation, the presence of its top at about 645 metres below ground surface, and a thickness of 47.8 metres in SB_BH01 (DesRoches et al. 2022a). In SB_BH02, the top of the Cobourg Formation occurs about 670 metres below ground surface and its thickness is 46.7 metres (Cachunjua et al. 2023). The difference in depth to the top of the Cobourg Formation is a function of the varying surface topography and the gentle west-southwest inclination of the sedimentary layers at the site scale. At both borehole locations, the Cobourg Formation is overlain by around 220 m of Ordovician shales and underlain by more than 150 m of Ordovician limestones. The Ordovician limestones are in direct contact with the underlying Precambrian bedrock (Figure 3.3; DesRoches et al. 2022b, Cachunjua et al. 2023).

The overall thickness of the Ordovician aged rocks encountered in the boreholes beneath the site, and the drilled depth to the top of the Cobourg Formation, are within metres of the predictions based on the regional model of Carter et al. (2021). These site-specific results are also consistent with previous results from Phase I Preliminary Assessment studies (Geofirma 2014). This comparability illustrates the large lateral extent and uniform thickness of the Ordovician rocks, and the Cobourg Formation in particular, regionally and beneath the South Bruce Site. An example of the Cobourg Formation from core recovered beneath the South Bruce Site is shown in Figure 3.4.

The updated 3D stratigraphic model (Carter et al. 2021) predicted that the Cambrian sandstone unit pinches out (i.e., becomes very thin to non-existent) beneath the South Bruce Site. Consistent with this prediction, the Cambrian sandstone unit was not encountered in either of the two boreholes drilled at the site. As will be discussed in Section 3.4 below, the lack of a Cambrian unit contributes to a different hydrogeological character at the base of the sedimentary sequence beneath the South Bruce Site than was encountered at the Bruce nuclear site.

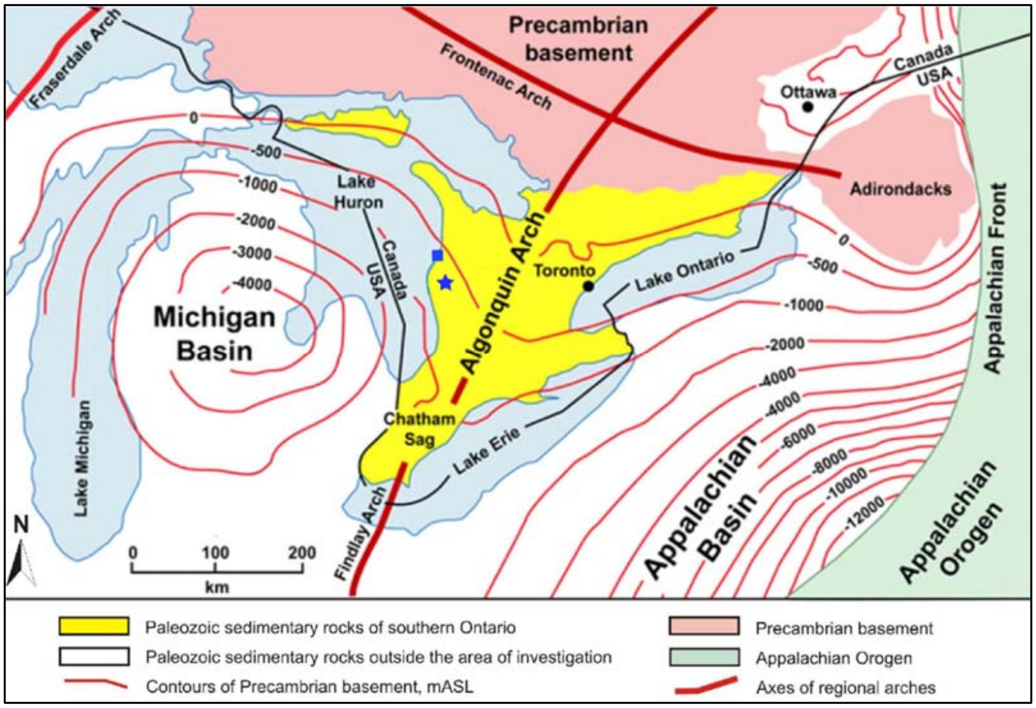


Figure 3.1: Geological features of southern Ontario (modified from Johnson et al. 1992). Blue star indicates location of South Bruce Site and blue square indicates location of the Bruce nuclear site.

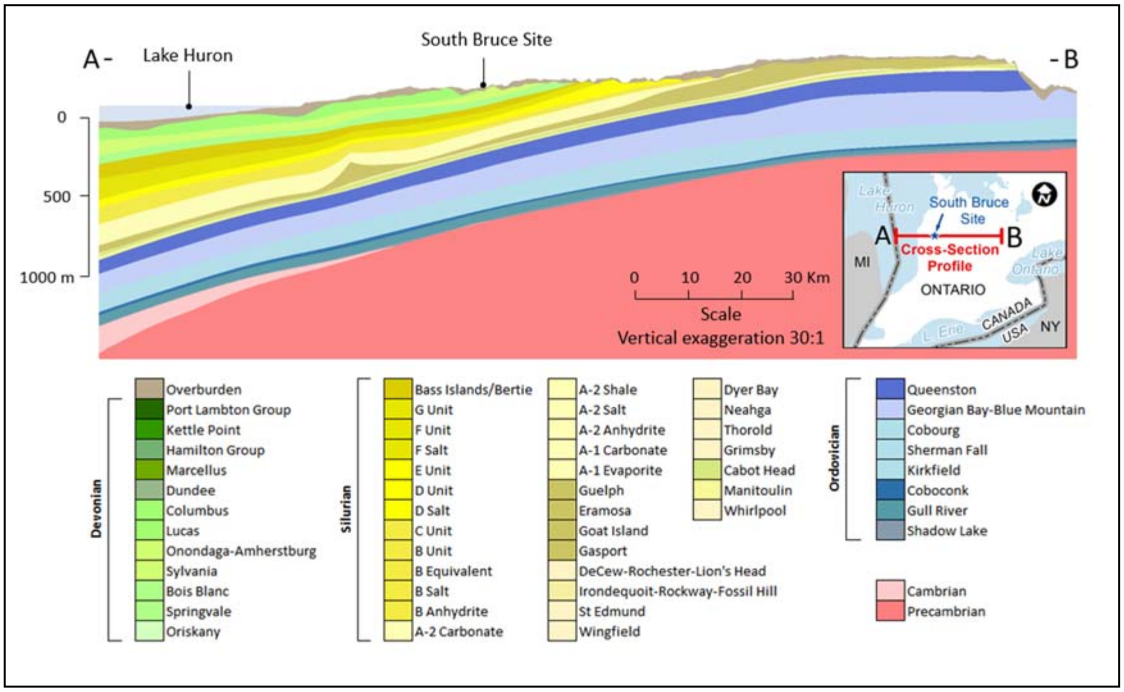


Figure 3.2: Vertical cross-section of the Michigan Basin in southern Ontario showing the main rock formation layers (based on Carter et al. 2021). A 30x vertical exaggeration has been applied to the section to illustrate the layering. True formation dips are uniformly < 1° to the southwest.

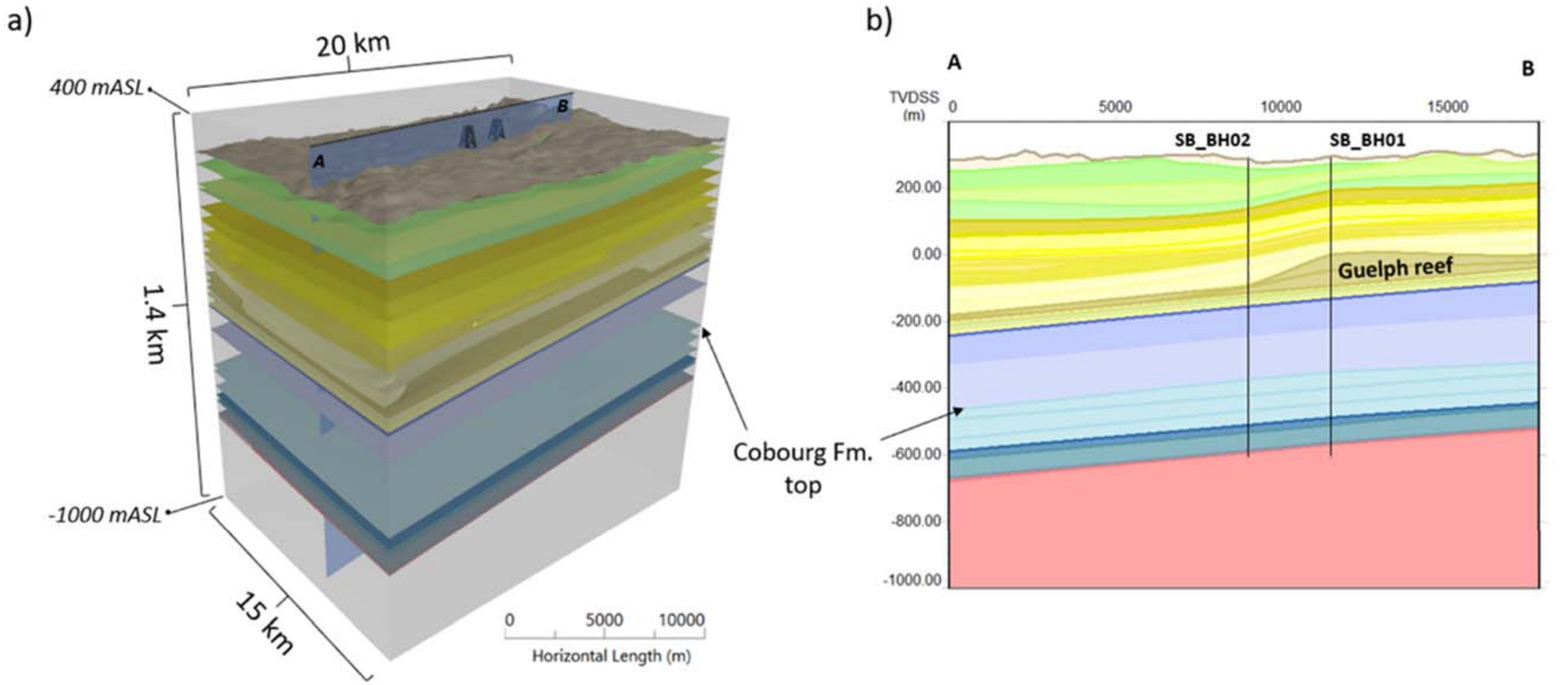


Figure 3.3: South Bruce geological model. a) 3D oblique view of stratigraphic formation top surfaces with top of Cobourg Formation identified. b) cross section view through model intersecting boreholes SB_BH01 and SB_BH02 and showing the Silurian-age reef within the Guelph Formation. Refer to Figure 3.2 for colour legend. Vertical exaggeration is 15x (from DesRoches et al. 2022a).

Figure 3.4: Examples of Cobourg Formation from beneath the South Bruce Site from approximate 669 m depth in SB_BH01. Each piece of core is 83 mm in diameter.

A newly developed South Bruce 3D model (Figure 3.3; DesRoches et al. 2022a), and preliminary results from the 3D seismic survey (Figure 3.5), support the understanding that the Cobourg Formation is laterally consistent and has a uniform thickness beneath the South Bruce Site. The 3D seismic survey results do not suggest the presence of any active geological features (e.g., faults) or unfavourable heterogeneities in the Cobourg Formation at the South Bruce Site that would constrain the volume of usable rock for repository construction.

The 3D seismic survey also advanced the understanding of the thickness and extent of the Silurian reef (Guelph Formation). The thickness of the Guelph Formation reaches approximately 70 m at the apex of the irregularly shaped reef structure that underlies the eastern part of the South Bruce Site (Figure 3.5). Elsewhere across the site the Guelph Formation is uniformly much thinner, including in SB_BH01 where the logged thickness of the Guelph Formation is five metres (Cachunjua et al. 2023). While the reef itself does not directly impact the containment and isolation properties of the underlying Ordovician-aged formations, its geometry and character will continue to be investigated to support repository design and to accurately model surface and shallow groundwater movement.

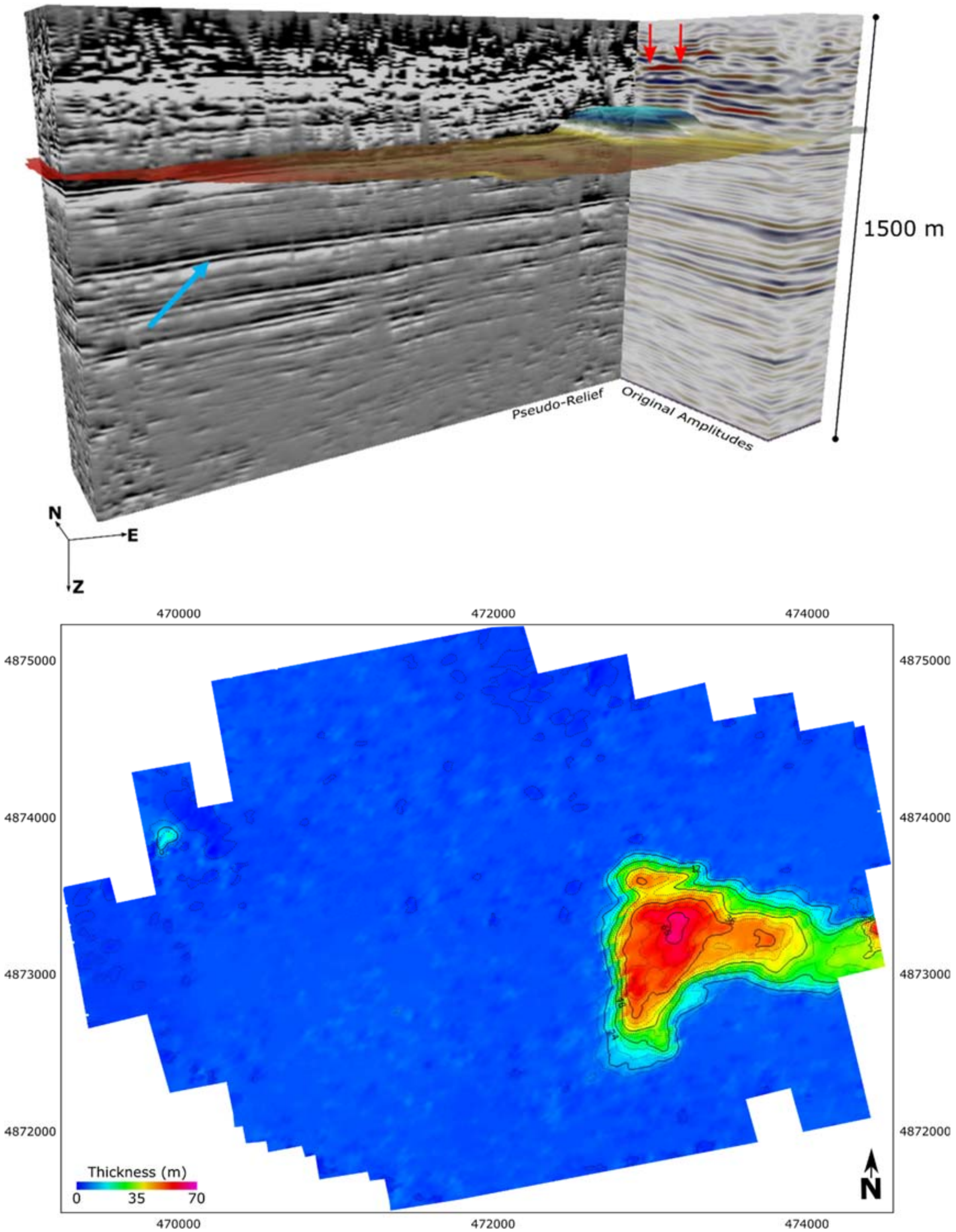


Figure 3.5: Top: View through a portion of processed data from the 3D seismic survey showing the top of the Guelph Formation in colour-shaded relief, including the geometry of the reef structure indicated by the blue shaded region beneath the red arrows. The top of the Cobourg Formation is indicated by the tip of the light blue arrow. Bottom: True stratigraphic thickness of the Guelph Formation as derived from seismic interpretation.

3.2 Depth and Volume of Competent Rock

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

Collectively, the geoscientific information, as described in Section 3.1, indicates that the Cobourg Formation, and the bounding Ordovician shale and limestone layers, are sufficiently deep to provide containment and isolation. It is also important to note that the greater than 200 m of Ordovician shales represent a barrier with sufficient thickness that will isolate the Cobourg Formation from having any connection to the overlying younger sedimentary rocks, including the reef of the Guelph Formation.

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 major faults and unfavourable heterogeneities, such as regions of high groundwater flow, including the Guelph Formation reef structure. As noted above, the Ordovician shales provide a sufficient barrier between the Cobourg Formation and the younger sedimentary units at shallow depths beneath the South Bruce Site. There is currently no evidence for major faults in the vicinity of the site.

The potential deep geological repository site in South Bruce was defined by signed agreements with landowners in South Bruce. Figure 3.6 shows the over 1,500 acres of land secured by the NWMO that define the potential repository site, in relation to the locations of the deep boreholes SB_BH01 and SB_BH02, and shallow groundwater monitoring wells. This area is sufficient for the repository.

As described in Section 3.1, the Cobourg Formation is laterally extensive beneath the site, and about 47 m thick. Given the thickness and extent of the Cobourg Formation, the presence of more than 200 metres of overlying Ordovician shales, and the extent of land secured by the NWMO, there is sufficient volume of suitable rock in the South Bruce Site to contain and isolate a deep geological repository.

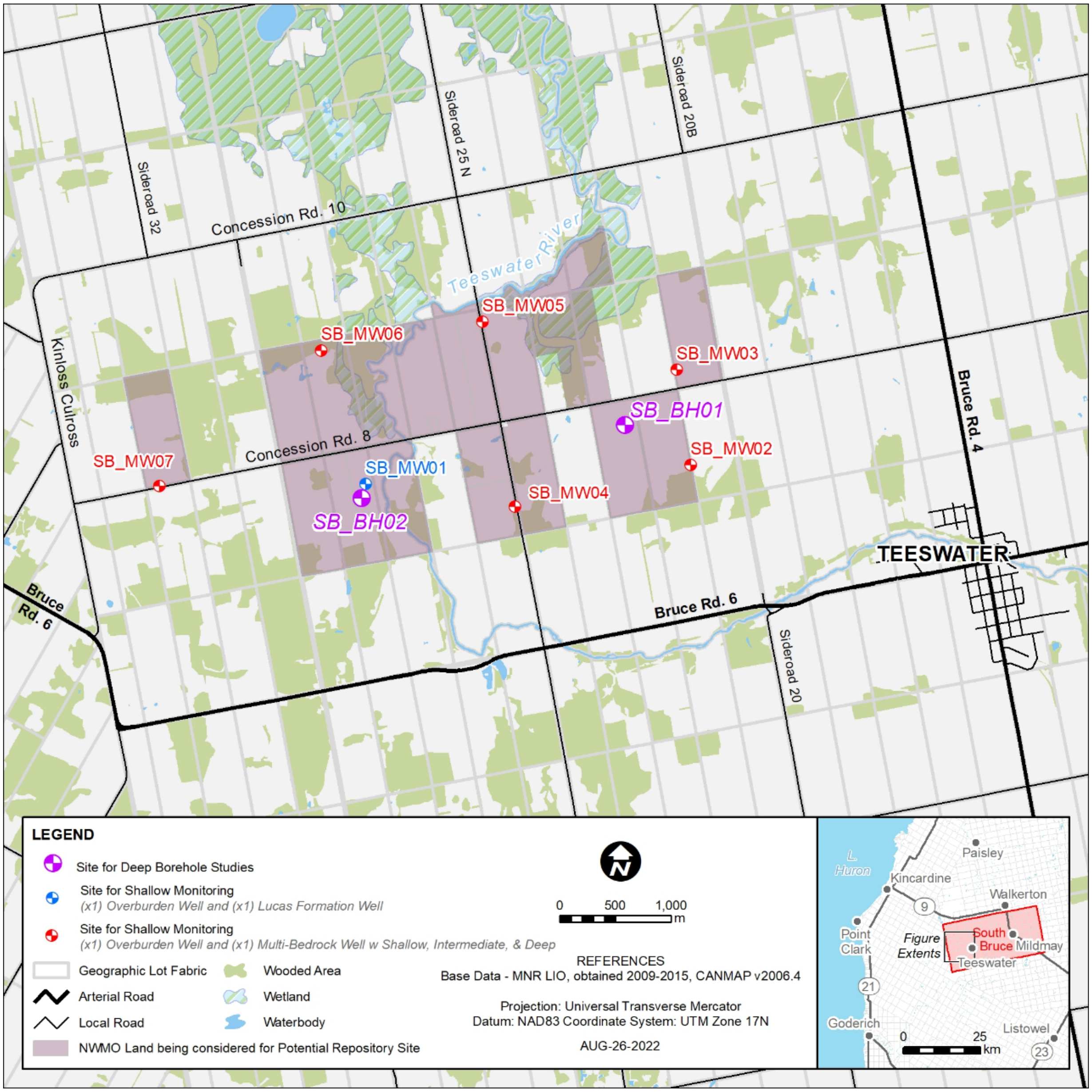


Figure 3.6: Location of the South Bruce Site, including NWMO owned or leased lands shaded in purple. The surface locations of the two deep boreholes, SB_BH01 and SB_BH02, and shallow groundwater monitoring wells (SB_MWXX), are also shown.

3.3 Composition of Rock, Groundwater and Porewater

The mineralogy of the rock, and the geochemical composition of the groundwater and porewater at repository depth should 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 therefore recent 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 at the repository level should also be low in order to maintain the durability of the engineered barrier system. Highly saline groundwater/porewater at repository depth, although a favourable attribute from the point of view of indicating isolation of the deep groundwater system from fresh water in the shallow subsurface, can have complex effects with respect to 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 discussed later in Section 3.5.

3.3.1 Rock Composition and Porosity

Site-specific data on the mineralogy (i.e., mineral content) of the Cobourg Formation is being gathered from core samples collected in the boreholes, and results are not yet available. Preliminary core logging data from the boreholes confirmed that the Cobourg Formation limestone includes clay and other minerals, which is consistent with observations from investigations conducted at the Bruce nuclear site as part of OPG's previously proposed Deep Geological Repository for Low & Intermediate Level waste (NWMO 2011; Intera 2011). Mineralogical analyses conducted at the Bruce nuclear site showed that the Cobourg Formation is mostly composed of calcite, with subordinate amounts of dolomite, quartz, and illite. Minor to trace amounts of the sulphide-bearing mineral pyrite were identified in the Ordovician-aged sedimentary formations (Intera 2011). Given the lateral consistency of the Ordovician formations in southern Ontario, a similar mineralogy encountered at the Bruce nuclear site is expected at the South Bruce Site. These low concentrations of sulphur-bearing minerals are not likely to impact the durability of the copper within the engineered barrier system.

At the Bruce nuclear site, the average total porosity of the Ordovician shales is 7.2 volume % and the average total porosity of the Cobourg Formation is 1.5 volume % (Intera 2011). Similar low porosity values are expected to contribute to the retardation of radionuclide movement through the Ordovician rocks at the South Bruce Site.

3.3.2 Groundwater and porewater composition

Where possible, groundwater samples were collected from different formations in the boreholes and sent to laboratories for geochemical analysis. Information on the geochemical composition of water at depth is also obtained from the minute amount of porewater extracted from core samples collected at different depths, including from the Cobourg Formation, and overlying and underlying Ordovician formations. The analysis of South Bruce Site data is ongoing. Some results are discussed in the next section in relation to their hydrogeological significance.

Information on the porewater chemistry from data collected at the Bruce nuclear site can be considered as an analogue for the South Bruce Site, given the proximity and lateral continuity of the sedimentary formations. Analyses of porewater samples from the Ordovician-aged sedimentary formations at the Bruce nuclear site indicated that the fluids (including high salinity brines and gases) had resided within the rock for hundreds of millions of years, consistent with a deep groundwater system having been isolated from the shallow groundwater system for a very long time. At repository depth, conditions are reducing (i.e., dissolved oxygen is not present in any of the Ordovician formations, including the Cobourg Formation). Based on this, oxidizing conditions are not expected at repository depth at the South Bruce Site.

At the Bruce nuclear site, the analysis of a Cambrian groundwater sample was used to understand the sulphide concentration expected at repository depth. The sulphide concentration in that Cambrian groundwater sample was less than 0.5 mg/L (Intera 2011). Similar low sulphide concentrations, which would therefore not likely impact the durability of the copper within the engineered barrier system, are expected in the deep subsurface at the South Bruce Site.

3.3.3 Summary

The majority of the rock and water chemistry properties expected to be encountered at repository depth at the South Bruce Site are unlikely to adversely impact the repository multi-barrier system. The expected high salinity conditions will require additional analysis regarding its potential effects on the engineered systems. However, it should also be noted that the overall containment and isolation properties of the geosphere are very likely to mitigate this. Based on the transferability of available information from the Bruce nuclear site, it is very likely that the properties of the rock and water chemistry at the South Bruce Site will promote the retardation of radionuclide movement.

3.4 Hydrogeological Regime

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

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

The ability of water to move through the rock was observed at site through two ways.

First, during the drilling of the boreholes at the South Bruce 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. In the two deep boreholes drilled in the South Bruce Site, opportunistic groundwater samples could only be collected from six different formations. These samples were collected from formations that are known to be permeable and are hundreds of metres above the proposed repository host rock formation. The deepest groundwater sample was collected at approximately 325 m below ground surface. This is more than 300 m above the Cobourg Formation. No appreciable groundwater was able to flow into the borehole from the Cobourg Formation, or the overlying Ordovician shales.

The primary source of information on the host rock's hydraulic conductivity is hydraulic packer testing in the deep boreholes. Packer testing was conducted in both boreholes in either 5 m or 20 m intervals, at different depths (Figure 3.7). Estimated horizontal hydraulic conductivities are extremely low within the Ordovician sedimentary rocks (shales shaded in dark and light purple and limestones in dark and light blue), including approximately 10^{-14} m/s in the Cobourg Formation. At shallower depths, above the Ordovician sedimentary rocks, hydraulic conductivity is more variable.

Information from the Bruce nuclear site has shown that in the Cobourg Formation, the horizontal hydraulic conductivities also have an average value of 10^{-14} m/s (NWMO 2011). The consistency in the results between the two sites reinforces the understanding that these extremely low permeability conditions are a general characteristic of the Cobourg Formation at depth, including beneath the South Bruce Site. Furthermore, model results suggest that vertical hydraulic conductivities were equivalent to or less than the measured horizontal hydraulic conductivities at the Bruce Site (Normani et al. 2017). For comparison, the hydraulic conductivity of pure sand ranges from 10^{-6} to 10^{-2} m/s; the estimated hydraulic conductivities in the Cobourg Formation at the Bruce nuclear site are over 1 million times smaller.

Additional information on groundwater flow was also obtained from other borehole testing (i.e., geophysical logging) and from long-term pressure monitoring at discrete intervals along some of the deep boreholes. This long-term pressure monitoring system was installed in SB_BH01 to obtain data on the natural fluid pressures within the different rock formations below the South Bruce Site. Estimated freshwater head pressure profiles for SB_BH01 are included in Figure 3.7. Data plotting to the left of the vertical dashed line indicate very low formation pressures relative to an assumed hydrostatic level. Data points are coloured by timing of pressure data collection, including from earliest to latest measurement dates (orange, blue, yellow, green, purple). As can be seen in the evolution over time, the pressure within the Ordovician interval, in particular around the Cobourg Formation, is still equilibrating. Low hydraulic conductivities are necessary in order to develop and preserve such underpressured conditions.

Similar underpressured conditions are present in the Cobourg Formation and bounding shale and limestone layers beneath the Bruce nuclear site. The presence of these underpressures was used as natural evidence that the Cobourg and its bounding layers have extremely low hydraulic conductivity across the entire Bruce nuclear site and any transport (movement) in these layers will be diffusion-dominated. Beneath the Bruce nuclear site these underpressures also transition into overpressures at the bottom of the sedimentary sequence in association with the presence of permeable Cambrian sandstone. This transition added an additional complexity to developing an understanding of the nature of these anomalously pressured conditions. Such overpressured conditions are not encountered beneath the South Bruce Site due to the absence of Cambrian sandstone.

Regardless of this distinct difference in stratigraphy, and resulting hydrogeological character, at the base of the sedimentary sequence between the two sites, it remains that the borehole geophysical logging and hydraulic packer testing, as well as pressure monitoring system which recorded data for 10 years, at the deep boreholes at the Bruce nuclear site (Intera 2011; NWMO 2011), can be used with confidence to support the understanding that the Cobourg and its bounding layers have extremely low hydraulic conductivity across the entire South Bruce Site. By inference, any transport (movement) in these layers will be similarly diffusion-dominated. Importantly, the lack of a Cambrian unit has an additional, favourable, impact on the deep hydrogeological conditions beneath the South Bruce Site.

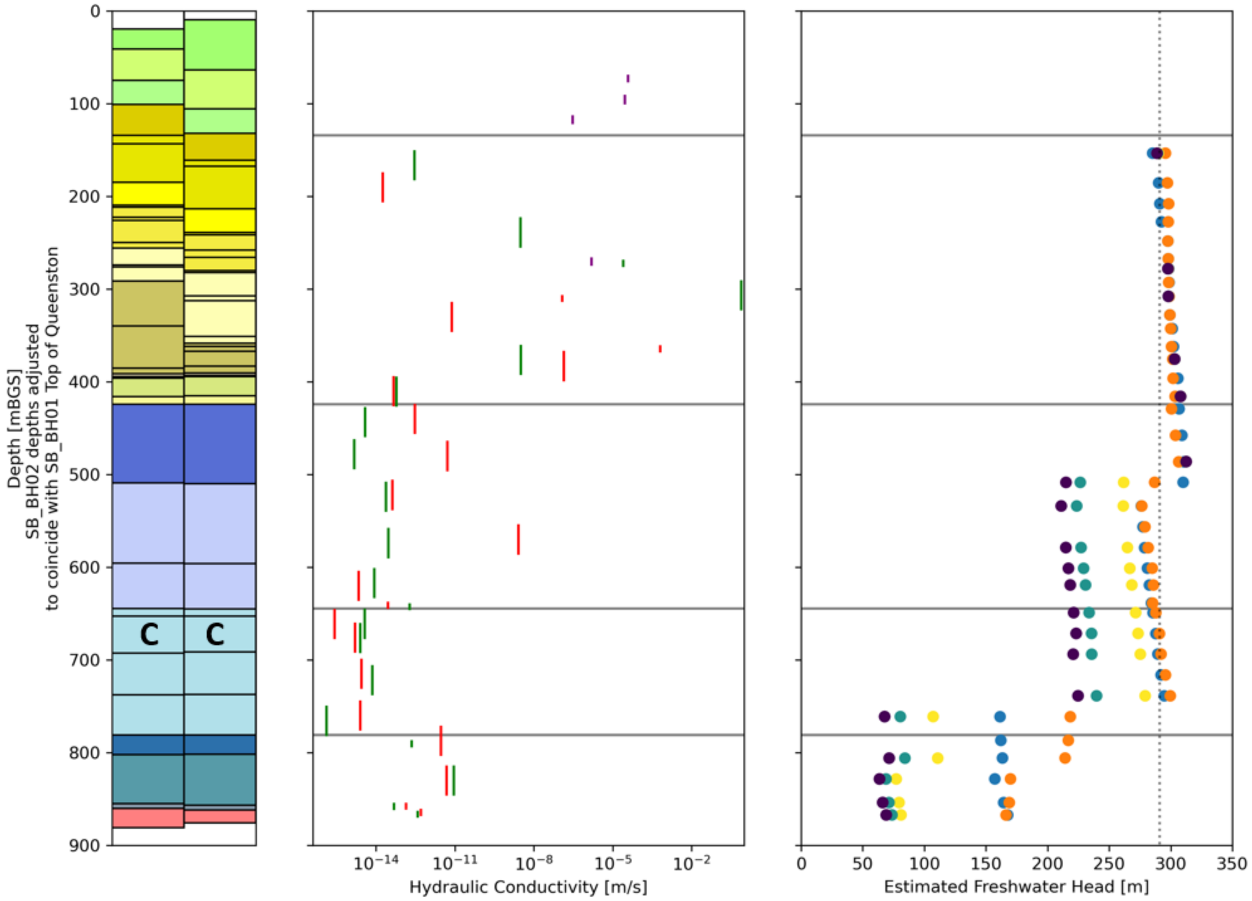


Figure 3.7: Left: simplified stratigraphy of SB_BH01 and SB_BH02 (see Figure 3.2 for colour legend; 'C' indicates Cobourg Formation). Centre: Hydraulic conductivity estimates for SB_BH01 (green) and SB_BH02 (red), highlighting the extremely low hydraulic conductivity throughout the Ordovician shales and limestones. Right: Estimated freshwater head pressure profiles for SB_BH01. Data points are coloured by timing of pressure data collection, from earliest to latest measurement dates (orange, blue, yellow, green, purple). Data plotting to the left of the vertical dashed line shows underpressured conditions throughout much of the Ordovician shales and limestones.

Groundwater and porewater chemistry results for the South Bruce Site, specifically chloride concentrations, are shown in Figure 3.8. Very low chloride concentrations in opportunistic groundwater samples (OGW, open circles), and porewater samples (PW, solid circles) are present in the near surface in both boreholes. This contrasts with very high chloride concentrations in porewater samples within the entire Ordovician sedimentary sequence at greater depths. Notably, no OGW samples were able to be collected below the Guelph Formation. At greater depths the rock has very few natural fractures and, consistent with the results shown in Figure 3.7, has extremely low permeability.

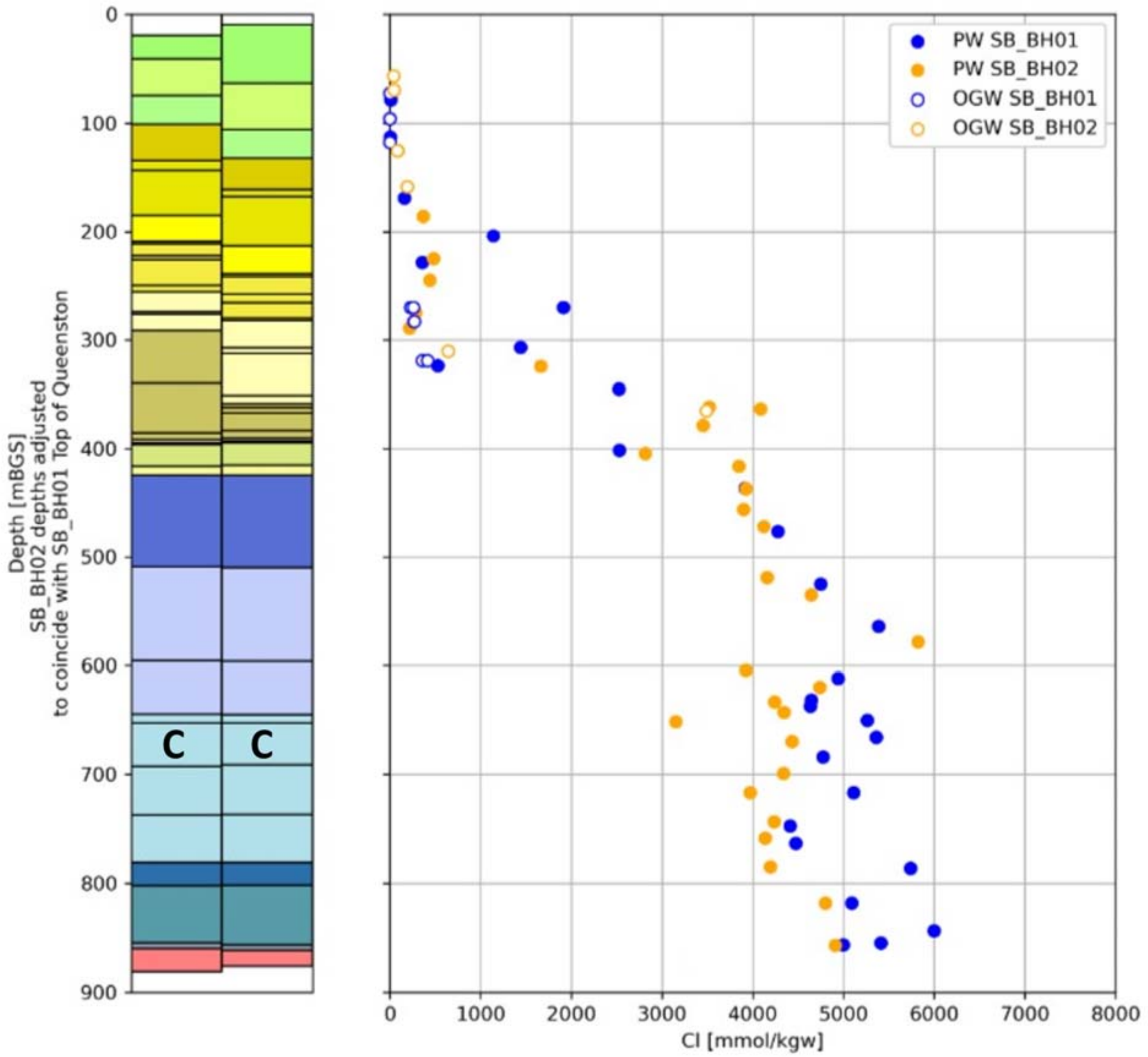


Figure 3.8: Left: simplified stratigraphy of SB_BH01 and SB_BH02 (see Figure 3.2 for colour legend; 'C' indicates Cobourg Formation). Right: Chloride concentrations from opportunistic groundwater (OGW) and porewater (PW) samples for SB_BH01 and SB_BH02.

At the Bruce nuclear site, groundwater and porewater were observed to be increasingly saline below 200 m depth, with the exception of one aquifer unit at ~325 m depth that had lower salinity. This showed evidence of recharge within the last 10,000 years in that one aquifer. There was no evidence of infiltration of glacial or recent meteoric water into the underlying Ordovician formations. High salinity can be an indicator of lower rates of mass transport, as a result of the associated increase in fluid density. The presence of high salinity conditions, as shown in Park et al. (2009), can indicate a hydrogeologically stable environment at depth (i.e., low rates of mass transport between the shallow and deep groundwater systems).

Similarly, at the South Bruce Site, a shallow hydrogeochemical zone confined to the upper approximately 200 m of bedrock, and a deep hydrogeochemical zone within the Ordovician-aged bedrock, contain fluids with different major ion chemistry and isotopic composition, and have no direct connection. Between the shallow and deep hydrogeochemical zones is a broad transition zone. The chemistry of the deep hydrogeochemical zone is indicative of long retention times for the fluids (i.e., very old waters). Although measurements to date are limited, there is no indication in the fluid chemistry results to suggest that glacial meltwater has penetrated into the deep hydrogeochemical zone at the South Bruce Site. These results are favourable for providing confidence that a repository located within the deep hydrogeochemical zone will remain isolated from the near-surface, providing protection for shallow groundwater resources and the biosphere.

In summary, although analyses to date are limited, the site-specific hydrogeological and hydrogeochemical information, shown in Figure 3.7 and Figure 3.8 respectively, suggest that a hydrogeologically stable environment, with low rates of mass transport, as demonstrated to be present beneath the Bruce nuclear site, is also present in the Ordovician-aged bedrock beneath the South Bruce Site.

3.5 Bedrock Stresses, and Geomechanical and Thermal Properties

The Cobourg Formation, which is the identified host rock, must be strong enough to withstand natural stresses as well as stress changes induced by the presence of the repository. 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 residual heat from the used fuel containers. These are discussed below.

Site-specific geomechanical and thermal data has been obtained from the current borehole drilling and testing program at the South Bruce Site. While there are only few results, there is a large volume of geomechanical property data available from detailed drilling and testing investigations at the nearby Bruce nuclear site (NWMO 2011; Golder Associates 2013), from regional compilations of geomechanical data (NWMO and AECOM Canada 2011; Golder Associates 2003) and from similar rocks reported in the literature (Clauser and Huenges 1995; Sass et al. 1984).

It is reasonable to assume transferability of the geomechanical and thermal properties from these sources to the South Bruce Site based on the lateral traceability and predictability of the sedimentary rock formations in southern Ontario. The geomechanical and thermal properties of the sedimentary rocks at the South Bruce Site are expected to be similar to those measured at the Bruce nuclear site and elsewhere in southern Ontario.

3.5.1 Bedrock Stresses

Bedrock stresses are measured underground, for example in boreholes, and result from the natural forces acting on the bedrock. Understanding the magnitude and direction of stresses in the bedrock is an important input for the design of the repository, specifically when aligning the orientation of the rooms and panels of the repository to optimize stability. At present, there are no direct measurements of stresses for the sedimentary rocks at the South Bruce Site. During detailed site characterization site-specific stress measurements will be carried out to refine the repository layout.

Information on the stress conditions expected to exist in the sedimentary rocks beneath the South Bruce Site is indirectly available from regional summaries of measurements made in the surrounding Appalachian and Michigan Basins (NWMO and AECOM 2011), from behaviour of borehole core and the borehole walls at the Bruce nuclear site, and from numerical modeling to develop a preliminary stress model for the Bruce nuclear site (NWMO 2011). Corkum et al. (2018) summarize the current understanding of the in situ stress state for sedimentary bedrock in southern Ontario, including from the sources listed above.

The available regional information on the distribution of principal stresses with depth in the Appalachian and Michigan Basins indicate the presence of high horizontal compressive stresses, where both principal horizontal stresses are greater than vertical stresses. These regional data also indicate that the maximum horizontal in-situ stress is consistently oriented in a northeasterly to east-northeasterly direction (NWMO and AECOM Canada 2011). Analysis of borehole ellipticity data from the Bruce nuclear site suggests a similar direction of maximum horizontal stress for the sedimentary rocks (NWMO 2011).

3.5.2 Rock Mechanical Properties

To date, data on the strength of the Cobourg Formation is mainly based on laboratory testing of intact core samples from the Bruce nuclear site, and limited laboratory testing of rock samples from rock quarries where the Cobourg Formation is exposed at surface.

Based on the available regional data, the Cobourg Formation is sufficiently mechanically strong. Site-specific measurements made on core retrieved from the deep boreholes at the South Bruce Site yield a mean (average) uniaxial compressive strength (UCS) of 104 MPa. This value is very similar to the average UCS of 113 MPa for the Cobourg Formation at the Bruce nuclear site (NWMO 2011). Average mechanical properties of the Cobourg Formation from surface samples collected at other locations in southern Ontario indicated a uniaxial compressive strength of 72 MPa (NWMO and AECOM Canada 2011).

3.5.3 Rock Mass Properties

In addition to determining the mechanical properties at the core sample scale, it is also important to assess the structural integrity of the rock mass, which refers to a larger scale representation of the bedrock, considering the presence of fractures, weathering, and alteration. A significant presence of these features could have a negative effect on the integrity of the rock mass. Site-specific rock mass properties will be obtained mostly from core logging and downhole testing (i.e., geophysical logging) activities, which are currently underway at the South Bruce site.

Data on rock mass properties of similar sedimentary rocks are available from studies completed at the Bruce nuclear site (NWMO 2011; NWMO and AECOM Canada 2011). Golder Associates (2003) estimated rock mass classification ratings in common usage for geomechanics purposes for selected rock formations based on shallow bedrock excavation experience in southern Ontario.

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%.

Overall, the rock quality of the Ordovician rocks at the South Bruce Site is considered to be excellent, averaging 98 % RQD in both boreholes. The RQD of the Cobourg Formation ranges between 97 and 100 %, and for the shale formations the RQD ranges between 84 and 100 %. It should be noted that the low RQD (84%) is only found in one core run in SB_BH01 in the Georgian Bay Formation and the RQD of other core runs ranges between 95 and 100%.

Similarly, at the Bruce nuclear site, the Upper Ordovician shale and limestone units, including the Cobourg Formation, are very sparsely fractured and of excellent quality (NWMO 2011). The RQD for all the Upper Ordovician shale formations is generally excellent (RQD of 90 to 100%) with occasional local zones of lower quality. Recorded RQD values tend to represent lower bounding values due to the intersection of vertical boreholes with sub-horizontal bedding layers.

The measured fracture frequency in the sedimentary rocks beneath the Bruce nuclear site was similar in all formations and ranges from 0 to 1.7 fractures per metre, with an average value of generally less than 0.3 fractures per metre. The fractures appear to be very tight and well sealed. Similarly, the Ordovician limestones have a rock mass designation of excellent, with RQD generally ranging between 90 and 100%. The fracture frequency in all Ordovician limestones is comparable. While fracture analysis is still on-going at the South Bruce Site, core logging observations indicate that in both boreholes there are very few natural fractures throughout the entire Ordovician sedimentary sequence.

Information available to date on rock mass properties from the South Bruce Site are consistent with results from investigations at the Bruce nuclear site and provide a good indication that the rock mass properties of the Cobourg Formation at the South Bruce Site are typical of strong sedimentary rocks.

3.5.4 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.

Initial thermal testing of core samples from the South Bruce Site focused on characterization of the Lower Silurian and Ordovician shale and carbonate rocks. Thermal conductivity of the Lower Silurian limestones, shales, and dolostones, based on testing of five samples, ranges between 1.69 and 3.16 W/(m.K). Thermal conductivity of the Ordovician shales, based on testing of six samples, ranges between 1.64 and 2.08 W/(m.K). For the Ordovician limestones, based on testing of 12 samples, the thermal conductivity ranges between 1.59 and 2.95 W/(m.K).

The shale and limestone layers beneath the South Bruce Site, in particular, share similar values as those found in the literature for similar rocks (Clauser and Huenges 1995; Sass et al. 1984). Rocks with these thermal properties would be capable of removing the decay heat from the fuel and withstanding thermal stresses induced by the repository (NWMO 2018; Guo 2018).

The calculation of a geothermal gradient for the South Bruce Site is still on-going. However, data collected during long-term pressure monitoring suggest that the temperature at 500 m depth is stabilizing to approximately 15 °C. Data from the Bruce nuclear site shows a natural geothermal gradient for the sedimentary sequence of about 14°C/km and an average rock and groundwater temperature at a depth of 500 m of +17 °C (NWMO 2018). These results are very similar and suggest that the conclusion that this gradient is suitable for repository design at the Bruce nuclear site (NWMO 2018) can also be transferred to the South Bruce Site.

3.5.5 Summary

The sedimentary rock sequence in southern Ontario is predictable, with uncertainty that is acceptable at this stage of site characterization, and the initial results from core testing indicate that the rocks beneath the South Bruce Site are not unusual in their mechanical and thermal behaviour. Based on the available site-specific data, as well as regional data, including data from the Bruce nuclear site, the Cobourg Formation and surrounding Ordovician layers beneath the South Bruce Site should be capable of removing the residual heat from the used fuel containers, and withstanding the natural and thermal stresses induced by the repository. On-going site-specific investigations are expected to confirm this.

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.

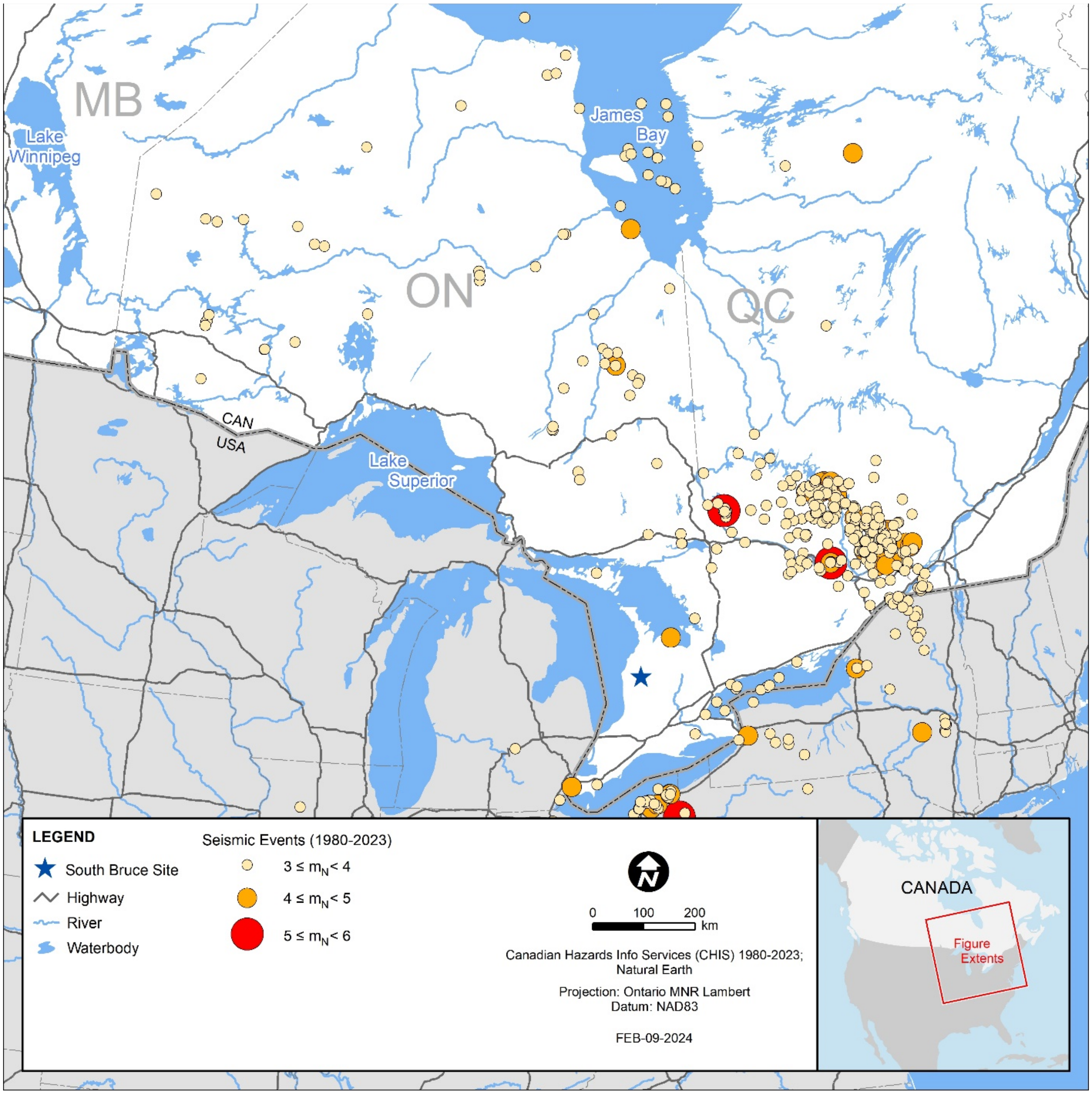
Each of these are discussed in the subsections below.

4.1 Seismicity

The South Bruce Site is located in a stable, seismically quiet setting overlying the Precambrian rocks of the Canadian Shield at the heart of the North American continent, away from tectonic plate boundaries.

The Canadian government has maintained a network of monitoring stations that record the location and magnitude of seismic events across the country. In southwestern Ontario, these have been supplemented with additional stations by OPG to improve the data coverage and accuracy. Figure 4.1 shows seismic activity for central Canada, including southwestern Ontario, as recorded by the Canadian Hazard Information Service (CHIS) between 1985 and 2023. Earthquakes are measured using the Nuttli Scale (m_N), which represents a modern refinement of the older Richter scale.

To date, in the CHIS dataset, there have not been any earthquakes above magnitude 3 m_N, a magnitude typically felt by most humans, recorded within 50 km from the South Bruce Site. The largest recorded earthquake in the area was a magnitude 4.3 seismic event centred 100 km northeast of the South Bruce Site.



Canadian Hazards Info Services (CHIS) 1980-2023; Natural Earth

Projection: Ontario MNR Lambert
Datum: NAD83

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

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

To date, no earthquakes above magnitude 1 ML have been observed in the NWMO microseismic dataset.

Microseismic monitoring will continue to record seismic events to aid in identifying the presence of any active faults in the regional area surrounding the South Bruce Site. Monitoring of small magnitude events (magnitude 3 ML and lower) provides information on the overall seismicity and geological structure of the local region surrounding the South Bruce Site. Ground vibrations associated with these small magnitude events are below the threshold considered to be able to cause structural damage to buildings. Further discussion regarding the regional faults identified on Figure 4.2 is included in Section 4.4 below.

Figure 4.2: All seismic activity recorded around the South Bruce Site from CHIS and from NWMO's microseismic network. Activity levels less than magnitude 3 are generally too low to be noticed by people, but can provide geological information about bedrock structure. Figure also shows location of regional faults in southern Ontario.

An analysis of the impact of future seismic events on the long-term stability of a repository, including a once in a million year 7.4 m_N seismic event was previously conducted for the Bruce nuclear site (Itasca 2011). The analysis found that seismic shaking would not induce damage to the host rock, other than potentially dislodging any additional damage to already fractured rock mass around the excavated openings. This result was expected because the host rock is strong, and because effects of seismic shaking underground are less than at surface. A similar study, recently initiated for the South Bruce site, is expected to reach similar conclusions.

4.2 Land uplift, subsidence and erosion

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

On a million-year timeframe, the main natural process that could possibly impact a repository at the South Bruce Site is expected to be future glacial cycles (Robin et al. 2020). These glacial cycles, expected to occur approximately every 120,000 years, can cause the land to depress (subside), uplift, erode, or to become covered with glacial deposits.

During glaciation, the bedrock is depressed by the weight of the icesheet. Afterwards the bedrock slowly rises back. The bedrock in the South Bruce area is presently uplifting at 1-3 mm per year, as the continental rock slowly recovers from the last ice age (Sella et al. 2007). This process is slow, and occurs with little variation in uplift rate around the South Bruce area, so by itself does not affect repository depth.

More significant is the possibility of glacial erosion. Studies by Bell and Laine (1985) estimate an average glacial erosion rate for Canada of 40–70 metres per million years, based on studies of past glacial cycles. Hallet (2011) provides an assessment of glacial erosion rates for southern Ontario, including the South Bruce area. The study by Hallet (2011) concluded that although uncertainties remain in ice sheet reconstructions and estimates of erosion, all lines of evidence indicate that, in southern Ontario, glacial erosion would not exceed a few tens of metres in 100,000 years with a conservative estimate of 100 m per 1 million years for the Bruce nuclear site. At the repository depth of 650 m, this level of erosion would not have a significant impact on the repository.

There are deep valleys through the sedimentary rock in the Finger Lakes region of New York state in the northern United States, about 500 kilometres from the South Bruce Site. These valleys were produced due to glacial processes occurring in a region of high topographic variation. This topographic variation is a long-lived feature of the Finger Lakes area and, during repeated glaciation, erosion was continuously focused in these developing valleys, ultimately producing the features seen today. Such regions with high topographic variation are not considered to be representative analogues for predicting the amount of glacial erosion expected in future in the South Bruce area.

A sediment-filled valley located along the west side of the South Bruce Site, just west of the Teeswater River, is about 50-m deep and trends southwesterly at surface. This is a paleo-channel and based on its sediment-filled nature was not an area of focused erosion in recent glacial cycles. Therefore, the presence of this sediment-filled valley is not likely to impact repository containment and isolation functions. However, this surficial feature will need to be characterized in order to support repository design, and to accurately model, and understand, surface and shallow groundwater movement.

In summary, there is currently no indication that the South Bruce Site location will experience extreme rates of erosion, uplift, or subsidence that would significantly perturb the deep geosphere over the next million years. Studies of bedrock erosion indicate that this type of process will be very unlikely to impact repository safety at a depth of around 650 m.

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 southwestern 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 not likely to significantly affect conditions at the repository depth, several hundred metres below surface.

In the future, 50,000 years or more, ice age conditions are expected to return. These conditions have occurred approximately every 120,000 years for the past million years, largely due to the nature of the earth's orbit around the sun. Recently completed modelling work suggests that in proximity to the South Bruce Site, the last ice age started about 115,000 years ago with the onset of permafrost development ahead of the advancing ice sheet, and ended about 10,000 years ago, when the ice retreated out of Ontario towards northern Canada (Figure 4.3).

The model results also suggest that, in proximity to the South Bruce Site, the last ice sheet reached a maximum thickness of approximately 2 km, and that permafrost attained a maximum depth of approximately 150 m below ground surface (Figure 4.3). These results provide site-specific refinement to previous modelling predictions that suggested there can be up to a 2.5 km thick ice sheet over Ontario (Peltier 2011; Stuhne and Peltier 2015, 2016).

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

Currently, the best indication of the impact of future glaciation on the South Bruce Site is evidence of how the site performed during past glaciations. Based on available data, there is no geochemical evidence found for the infiltration of glacial or recent meteoric recharge water into the host or bounding shale layers beneath the South Bruce Site. The Ordovician bedrock is extremely saline and exhibits no chemical traces of a glacial signature. In addition, numerical simulations from the Bruce nuclear site indicate: 1) that glacial perturbations do not alter the governing solute transport mechanisms within the deep groundwater system; and 2) that single and multiple glaciation scenarios, when modelled using regional and site-specific parameters, do not result in the infiltration of glacial meltwater into the deep groundwater system (NWMO 2011). Therefore, both site-specific South Bruce data and natural analogue modelling results for the Bruce nuclear site provide confidence that glaciations will have minimal impact at the South Bruce Site.

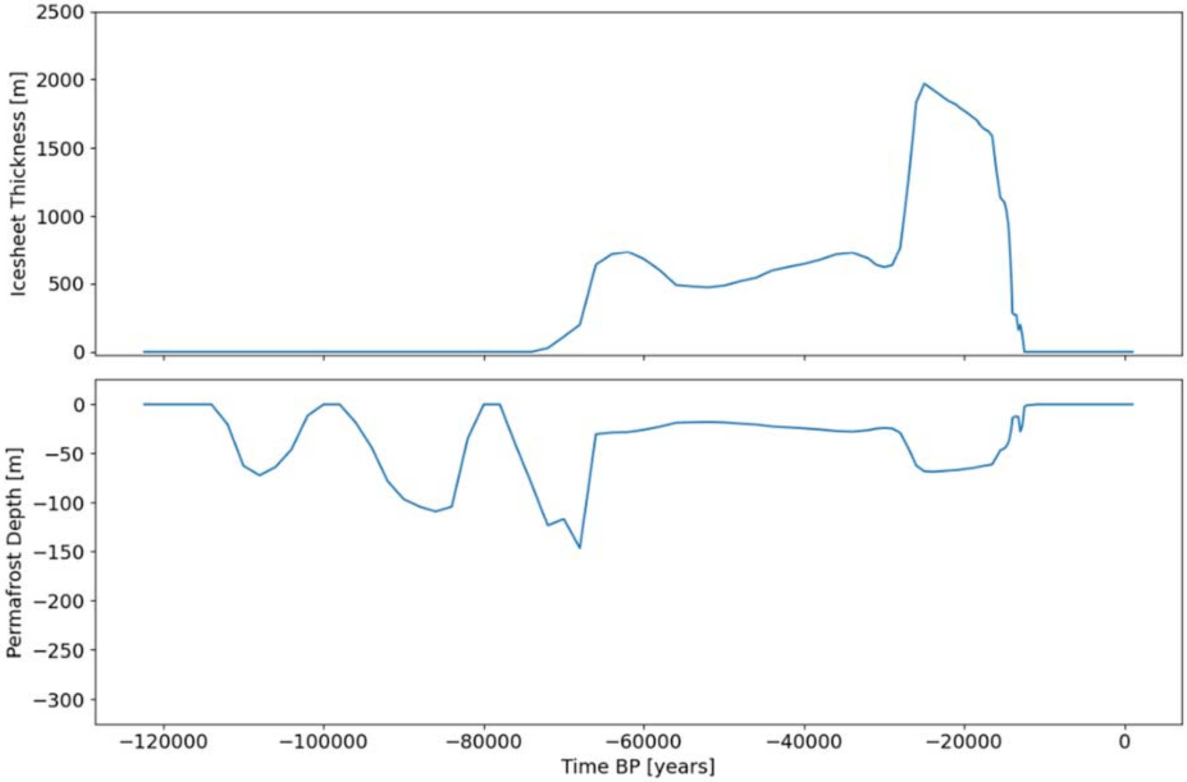


Figure 4.3: Evolution of ice sheet thickness (top) and permafrost thickness (bottom) for the region surrounding the South Bruce Site since 120,000 years before present (BP) based on the University of Toronto Glacial System Model (based on Stuhne and Peltier 2023)

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

In summary, multiple lines of evidence suggest that future climate change scenarios such as glacial cycles will impact the upper bedrock at the South Bruce Site but will have virtually no impact on the bedrock at the proposed repository horizon of 660 m below ground surface. At this depth, bedrock stresses and hydrogeochemical conditions are expected to remain stable during future glacial cycles.

4.4 Distance from geological features

The repository should be located at a sufficient distance from geological features such as zones of large-scale deformation or regional faults that could be potentially reactivated in the future, possibly through post-glacial earthquakes.

Regional, kilometre-scale, faults in southern Ontario are shown on Figure 4.2. As indicated in the legend to this figure, the faults are grouped based on observation of the youngest stratigraphic unit that is offset. The largest faults in southern Ontario are located near the northern edge of Lake Erie, many 10's of kilometres south of the South Bruce Site. The nearest known fault to the site is a fault located approximately five kilometres north of the South Bruce Site. This fault is interpreted to offset rocks as young as the Ordovician limestones. The fault is not sufficiently close to influence the integrity of the repository. The 3D seismic survey results also do not suggest the presence of any active geological features (e.g., kilometre-scale faults), at the South Bruce Site. Overall, based on all available information, the South Bruce Site is located at a sufficient distance from known geological features such as large-scale deformation zones or major regional faults.

The Cambrian unit is a permeable formation on top of the Precambrian (Canadian Shield) basement in some parts of the Michigan Basin. The Cambrian unit is important because it is known to be permeable, and because it can be under high pressure in places due to its deep confinement. The Cambrian unit was not intersected in the two boreholes drilled at the South Bruce Site, and as discussed in Section 3.4, that has a favourable impact on the deep hydrogeological conditions. Importantly, there are also low permeability limestone layers bounding the Cobourg Formation from below, regardless of whether the Cambrian is present or not.

The presence or absence of deep geological features in the subsurface beneath the South Bruce Site, including faults, will continue to be investigated by analysis of results from a recently completed 3D seismic survey, future inclined borehole drilling combined with additional core logging and borehole testing, and on-going microseismic monitoring.

As noted above, there is also a sediment-filled valley about 50-m deep located along the west side of the South Bruce Site. The sediment-filled valley is a shallow feature, which will not impact repository containment and isolation functions. However, this surficial feature will need to be characterized to support repository design, and to accurately model, and understand, surface and shallow groundwater movement.

5. FUTURE HUMAN INTRUSION

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

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

1. Should not be located within rock 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 requirements is discussed in the subsections below.

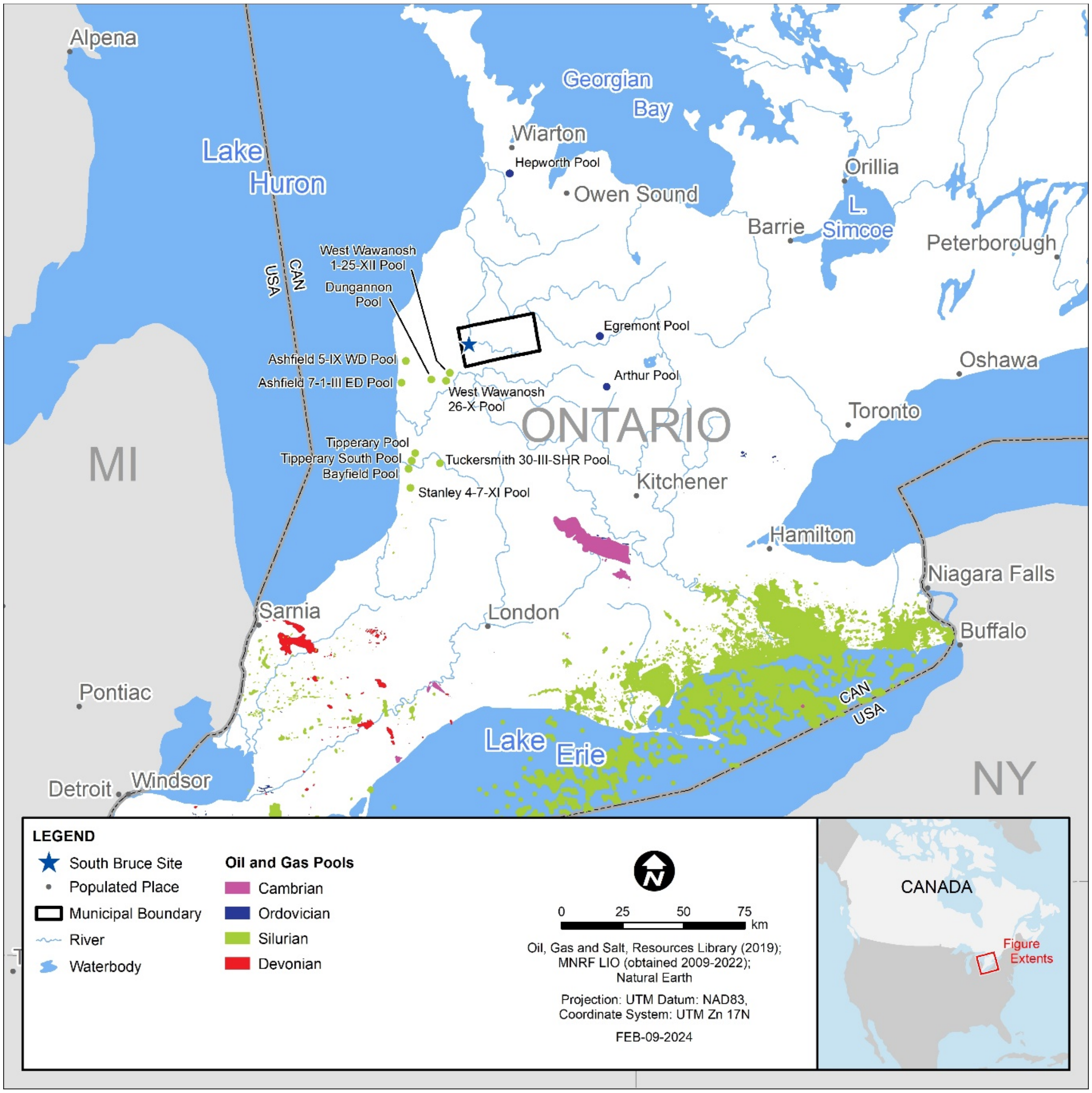
5.1 Economically exploitable natural resources

Natural resources assessed for the area broadly include petroleum resources (conventional and unconventional oil and gas), metallic mineral resources, non-metallic mineral resources (sand and gravel, bedrock resources and salt) and deep potable groundwater resources.

There are no known areas of active exploration interest for metallic mineral resources within the area, as evidenced by the lack of active mining claims (MNDM 2021a) and the lack of metallic mineral occurrences (Figure 5.1; MNDM 2021b). The Abandoned Mines Information System (MNDM 2018) and Mineral Deposits Inventory (MNDM 2021b) show that there are no current or past producing metallic mineral mines within the Municipality of South Bruce.

The South Bruce Site is located within an area that has been identified as a Sand and Gravel Resource Area with a large proportion judged to be of primary significance, and with an average deposit thickness of 5 m (Rowell 2012). There are also several discretionary limestone occurrences related to bedrock quarrying for aggregate and building stone use in the central portion of the Municipality*;* the potential for limestone as a resource for extraction, however, is limited to very shallow depths (typically less than 20 m) and is not considered as a constraint for repository construction.

A potential resource in the area is hydrocarbons. Commercial accumulations of hydrocarbons have been discovered in more than a dozen stratigraphic units throughout the sedimentary rock of southern Ontario. Figure 5.1 shows the distribution of active and former producing petroleum pools in southern Ontario based on the Oil, Gas and Salt Resources Library (OGSRL 2019). Most of the current exploration for oil and gas is concentrated within the geographic triangle between London, Sarnia and Chatham-Kent (AECOM Canada and Itasca Consulting Canada 2011) (Figure 5.1). The South Bruce Site is north of this area.



Oil, Gas and Salt, Resources Library (2019);
MNRF LIO (obtained 2009-2022);
Natural Earth

Projection: UTM Datum: NAD83,
Coordinate System: UTM Zn 17N

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Figure 5.1: Oil and gas producing pools in southern Ontario (OGSRL 2019)

There are no known oil and gas pools within the Municipality of South Bruce. Prior to the NWMO's work in this area, three previous exploration boreholes were drilled by exploration companies within the Municipality, which resulted in dry holes with no petroleum potential (Geofirma 2014).

An assessment of potential hydrocarbon resources in the regional area around the South Bruce Site was recently completed (Chen et al. 2019). The study focussed on two rock formations within this domain that are anticipated to be the most likely to contain oil or gas – the Collingwood and Rouge River shale rock units. They concluded that there was likely shale oil and gas within the domain, but the amounts were such that "the recovery factor for oil and gas in place resource was exceptionally low."

Overall, no known economically exploitable mineral resources, hydrocarbon resources or salt resources have been identified at the potential repository site. Visible oil and petroliferous odour are not uncommon in the sedimentary rocks across southern Ontario and are also observed in the rock cores from the South Bruce Site. However, there is no indication of economically significant concentrations of hydrocarbons at the site. This site-specific finding is consistent with the conclusions from the Chen et al. (2019) regional study.

Taken together, these findings indicate that while some resource potential may exist around the South Bruce Site, no known economically exploitable mineral resources have been identified at or near the proposed repository volume at the site.

5.2 Groundwater Resources

Information concerning groundwater use in the Municipality of South Bruce can be obtained from the Ontario Ministry of the Environment (MOE) Water Well Information System (WWIS) database (MOE 2013), as well as from regional groundwater studies and source water protection studies. All known water wells in the Municipality of South Bruce obtain water from overburden or shallow bedrock sources at depths ranging from about 3 to 163 metres below ground surface (mBGS; Geofirma 2014). Shallow bedrock is the most important source of drinking water in South Bruce, and is the primary source of most of the municipal water supplies located inland from Lake Huron.

The potential for groundwater resources within the repository host and bounding layers at the South Bruce Site is extremely low. Experience from other areas in southern Ontario, and from the studies completed at the Bruce nuclear site, has shown that there is no active deep groundwater system in the area due to the very low hydraulic conductivities of the Upper Ordovician units. Hydrogeological data from the Bruce nuclear site indicate that the deep groundwater system within the Upper Ordovician units is diffusion-dominated and isolated from the shallow groundwater system. In addition, the Bruce nuclear site exhibits a transition from fresh to non-potable and highly saline groundwater below approximately 200 mBGS.

During the drilling of the boreholes at the South Bruce 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 subsurface rock. In the two deep boreholes in the South Bruce Site, opportunistic groundwater samples could only be collected from six geological formations. These samples were collected from formations that are known to be permeable and are hundreds of metres above the proposed repository host rock formation. The deepest groundwater sample was collected at approximately 325 m below ground surface. This is more than 300 m above the Cobourg Formation. It was also saline and non potable. No appreciable groundwater was able to flow into the borehole from the Cobourg Formation, or the overlying Ordovician shales.

In summary, based on the available information, the South Bruce Site does not contain groundwater resources at repository depth that could be used for drinking, agriculture or industrial uses.

6. AMENABLE TO GEOLOGICAL SITE CHARACTERIZATION

The South Bruce Site must be understood sufficiently so that the repository can be appropriately designed and for there to be sufficient confidence that the site will perform as expected. However, as the host rock is not visible on surface, 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 that the host rock structure and properties are predictable and can be reliably characterized, with uncertainty that is acceptable at this stage of the project.

The South Bruce Site was identified as potentially suitable in part because the geometry and structure of the Ordovician host rock and bounding layers found at the South Bruce Site and throughout southern Ontario were expected to be sufficiently predictable and amenable to site characterization and data interpretation (e.g., Mazurek 2004).

Importantly, the site characterization activities at the Bruce nuclear site also indicated a high degree of similarity in geoscientific properties for all Paleozoic (sedimentary) formations between individual boreholes at the Bruce nuclear site (Intera 2011).

The lateral traceability of individual, near-horizontally layered and weakly deformed, bedrock formations, previously demonstrated at the Bruce nuclear site and at the regional scale, especially for the formations of Ordovician age (NWMO 2011; AECOM and Itasca Canada 2011), can now also be demonstrated for the South Bruce Site. The updated 3D geological model for southern Ontario continues to demonstrate the predictable nature of the Ordovician sedimentary layers across southern Ontario (Carter et al. 2021).

While the site characterization activities at the South Bruce Site are on-going, an assessment of the predictability of the sedimentary rocks beneath the site in the two boreholes, in comparison to the geological conditions encountered at the Bruce nuclear site and throughout the region, indicates that:

- The overall thickness of the sedimentary rock formations at site is broadly consistent with the regional stratigraphic model.
- The thickness and character of the Ordovician layers is approximately 435 m based on observations from the two boreholes, consistent with expectations.
- Cambrian sandstone was not encountered at the base of the boreholes.
- There are no significant hydrocarbon indicators, as expected.
- The general locations where opportunistic groundwater samples were collected is as expected.
- The high fracture frequency encountered in the upper 200 m of the boreholes, and extremely low fracture frequency throughout the Ordovician sequence, is as expected.
- The geomechanical and thermal properties are as expected.
- The extremely low hydraulic conductivities, and underpressured conditions, particularly in the Cobourg and bounding layers, are as expected.
- The high salinity conditions throughout the entire Ordovician sequence, in contrast to the very low salinity conditions in the near surface, is as expected.

While further analysis is required to confirm if the additional geoscientific properties of the sedimentary rocks beneath the South Bruce Site are consistent with their expected character, all indications to date suggest that they will be, especially with respect to the Cobourg and bounding sedimentary layers.

These studies provide confidence in the NWMO’s ability to characterize and understand the large-scale geometry, structure, geomechanical, thermal, hydrogeological and hydro-geochemical characteristics of the geology beneath the South Bruce Site.

7. REPOSITORY CONSTRUCTION, OPERATION, AND CLOSURE

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

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

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

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

7.1 Engineered Barrier System

7.1.1 Used Fuel Container

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

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

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

The container is designed to withstand the external pressure loads that would be experienced by the container during its design lifetime in a repository, including the external pressure loads caused by 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. At the South Bruce Site, the high salinity in the repository host rock is also being considered as part of the design optimization.

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 icesheet

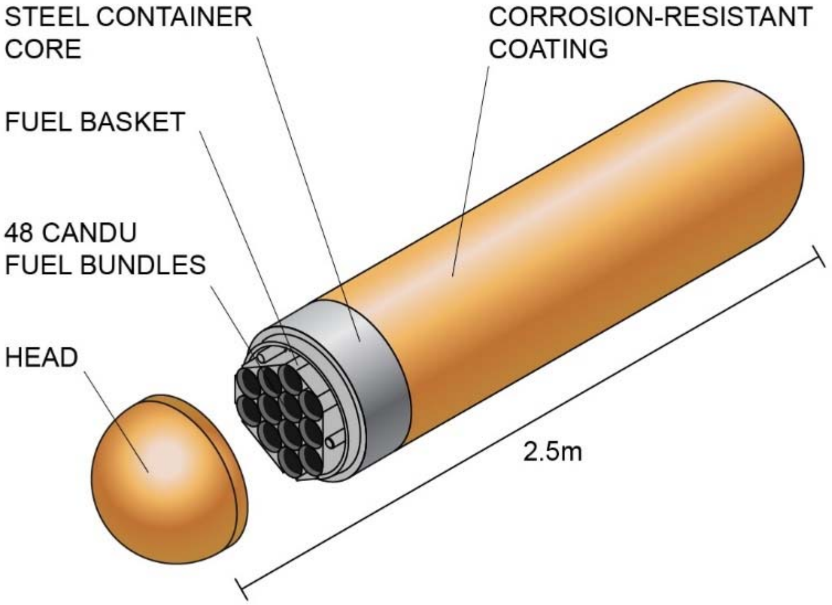

Figure 7.1: Illustration of reference copper coated Used Fuel Container

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

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

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

7.1.2 Buffer Materials and Sealing Systems

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

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

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

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

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

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

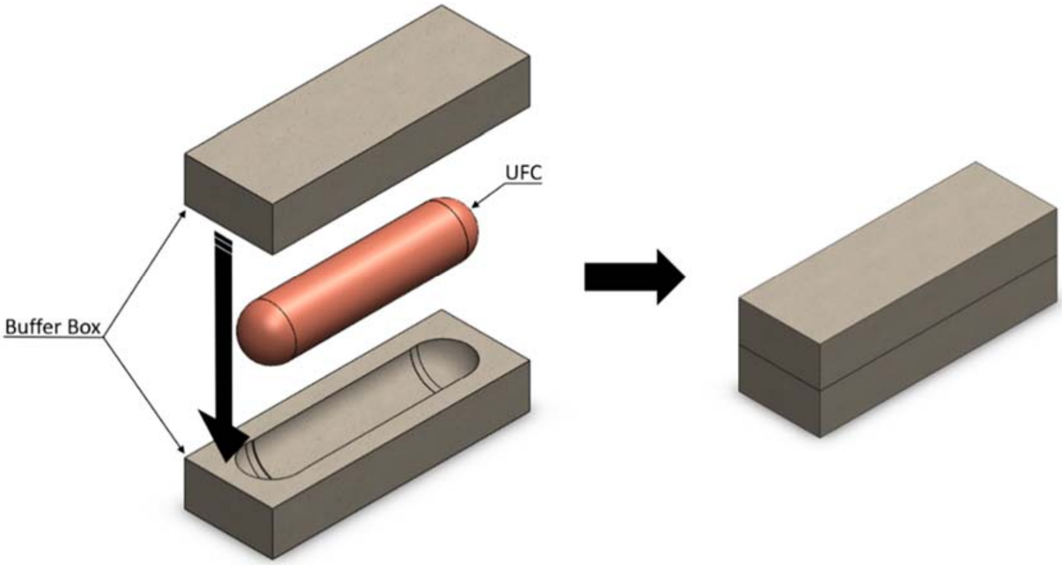

Figure 7.2: Used Fuel Container within a bentonite clay Buffer Box

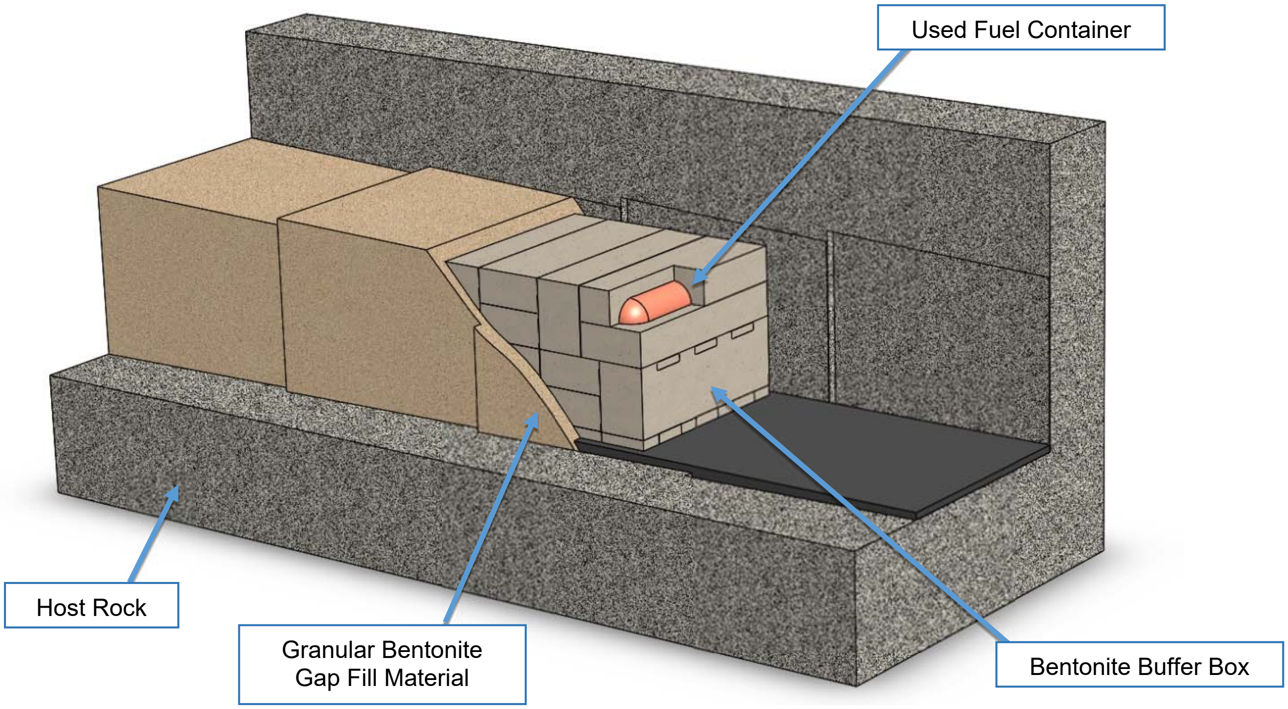

Figure 7.3: Cutaway Illustration of Placement Room Concept

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

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

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

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

7.1.3 Engineered Barrier Testing

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

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

Materials Testing

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

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

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

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

Container Fabrication and Testing

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

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

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

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

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

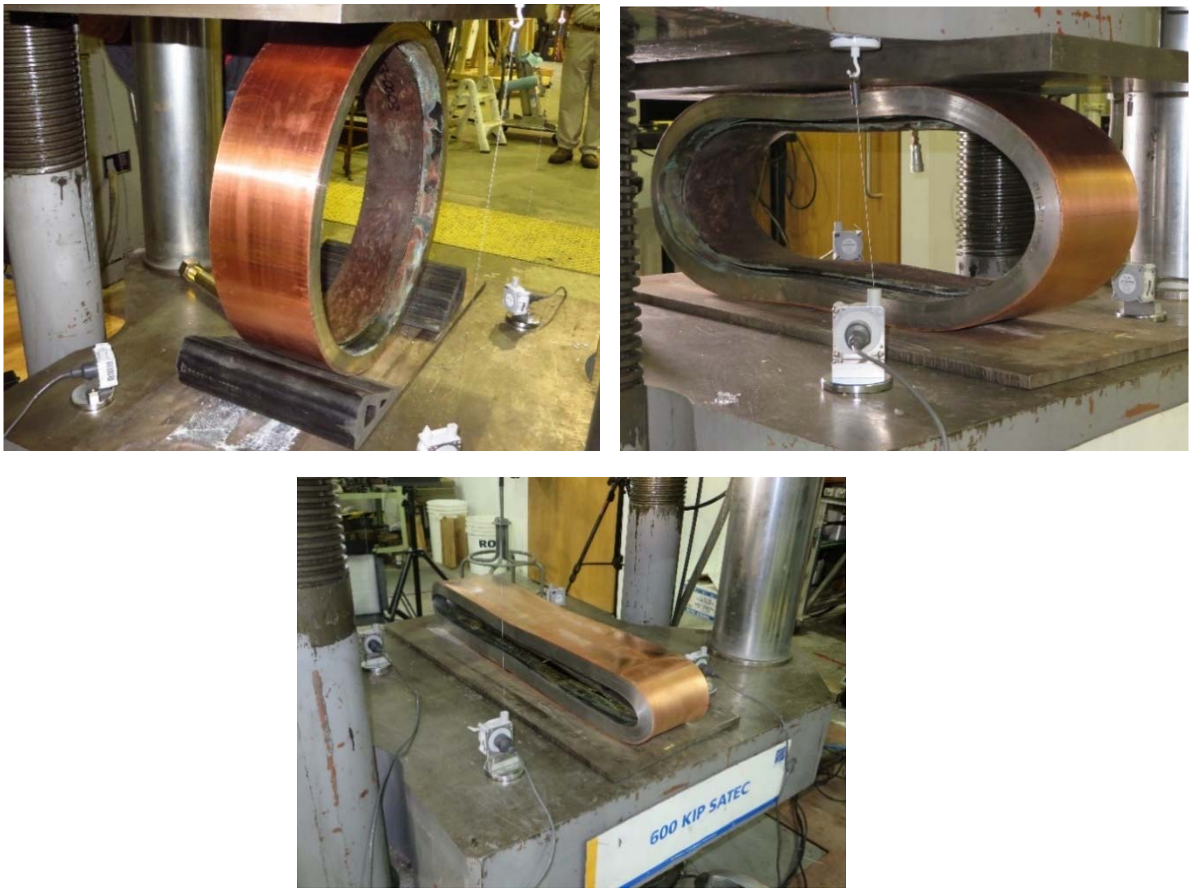

Figure 7.4: Used Fuel Container cross-section undergoing a beyond-design-basis crush test. Copper coating remained bonded to steel.

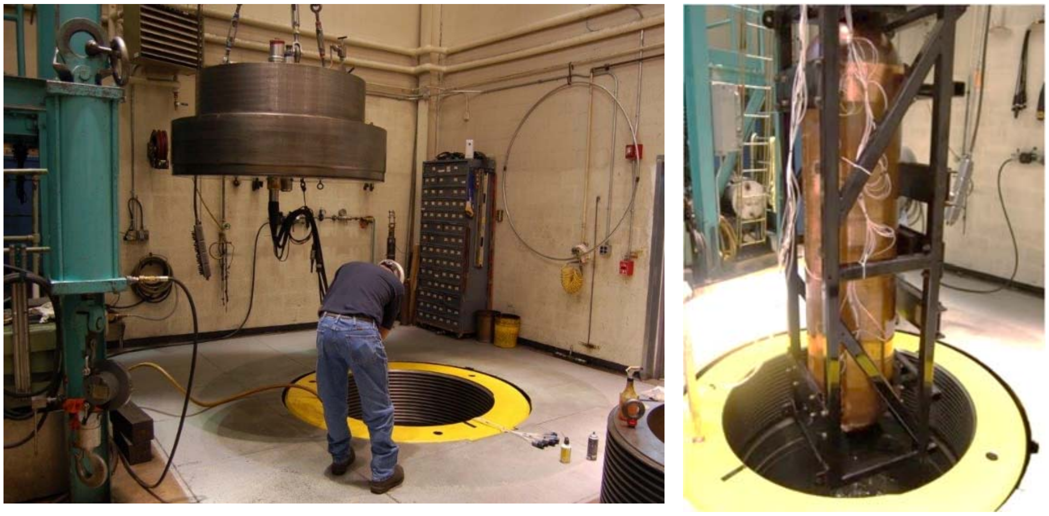

Figure 7.5: Copper coated prototype Used Fuel Container external pressure test at Penn State University in 2016. (Left) Test chamber lid being lowered into place; (Right) Container removed after experience more than 1.2 times the bounding design pressure; no significant change of configuration.

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

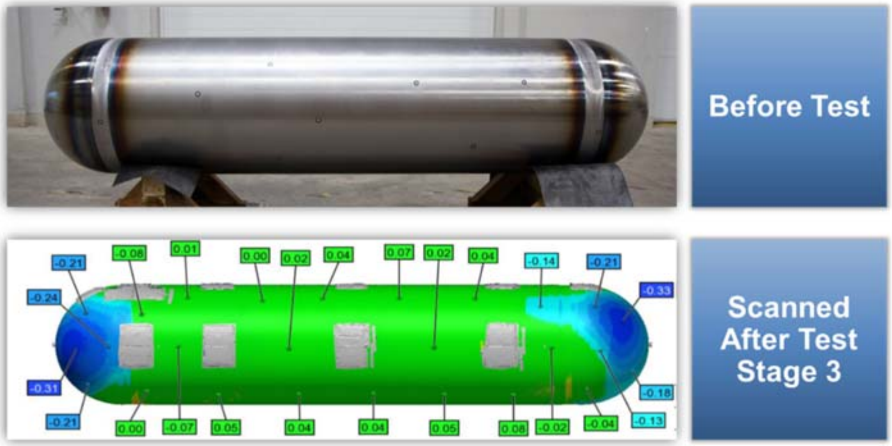

Figure 7.7: Steel prototype Used Fuel Container external pressure test. Photo shows container before and after 10 cycles of bounding design pressure including glacial load.

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

Buffer Fabrication and Tests

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

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

Figure 7.9: Prototype Buffer Box and Used Fuel Container

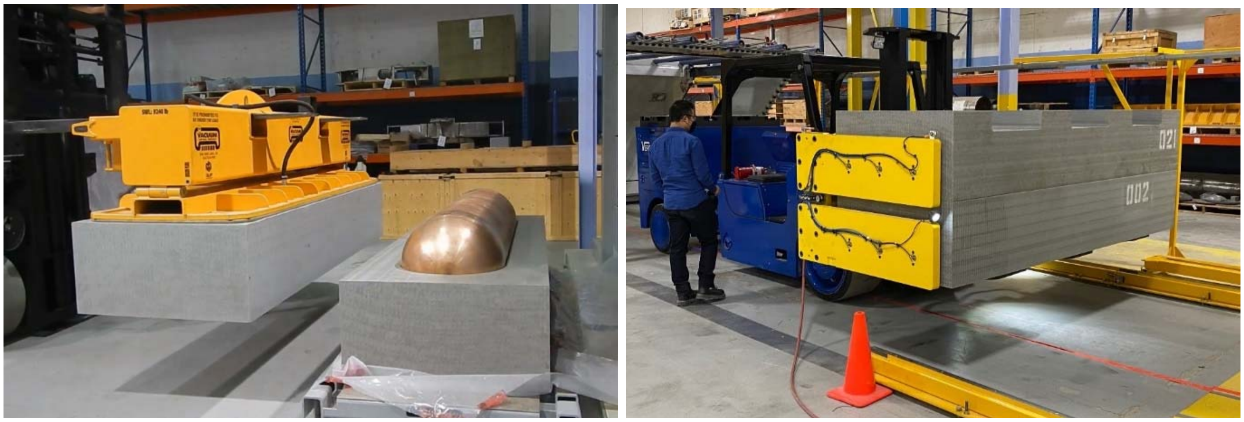

Figure 7.10: Bentonite handling: (Left) Using vacuum lift technology; (Right) Robotic forklift handling of buffer box

Placement Test

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

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

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

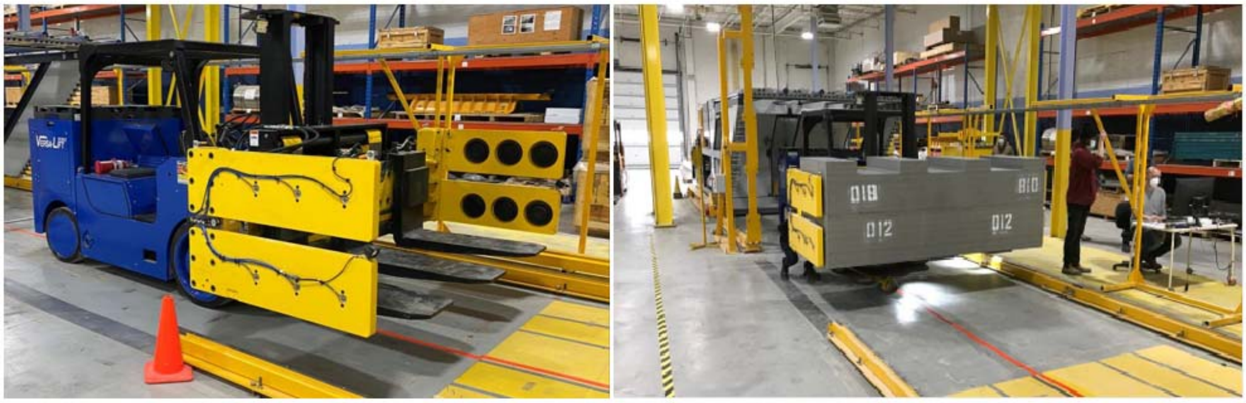

Figure 7.12: Buffer Box Delivery Equipment

Figure 7.13: Buffer Boxes in Placement Room

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

Figure 7.14: Gap Fill Material Delivery Equipment

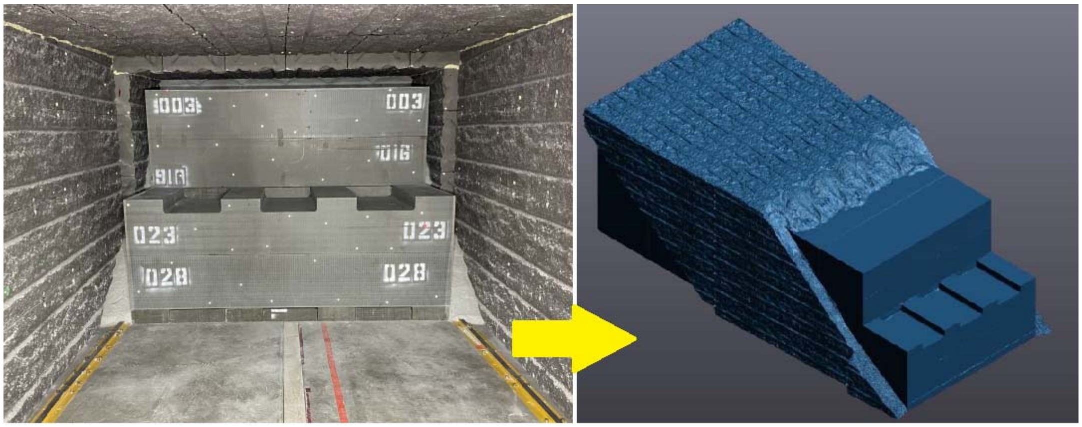

Figure 7.15: Gap Fill Material Placed around Buffer Boxes and 3D Scan

7.2 Underground Facilities

Based on the site-specific information, the NWMO is considering placing the repository within a depth range of about 650 m, in order to place it within the favourable Cobourg Formation rock.

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

7.2.1 Shafts

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

For the proposed repository depth and the nature of the South Bruce site, and consistent with Canadian mining experience, access to the repository would be through three shafts. These shafts are:
- Main Shaft Complex: for transfer of the used fuel container in buffer boxes;
- Service Shaft Complex: for movement of personnel, mining materials and excavated rock, as well as main air intake; and
- Ventilation Shaft Complex: for repository exhaust air; also provides secondary means of exit for personnel during an underground emergency.

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

The shaft sinking process in the sedimentary formation will likely require that top 180 to 200 m of bedrock has ground conditioning to limit the amount of groundwater inflow during shaft sinking. Ground conditioning would be achieved using well established techniques such as grouting or ground freezing. The concrete liner in this zone will also be designed to limit ground water into the finished shaft using mining best practice (e.g., hydrostatic concrete liner).

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

7.2.2 Central services area

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

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

7.2.3 Underground placement rooms and access tunnels

From the services area, twin access tunnels branch out forming various “arms” that lead into placement panels. The NWMO has selected this adaptive layout design to accommodate the geology and NWMO owned land, and to provide flexibility during construction and operation. An illustrative design is shown in Figure 7.16, from a prior generic sedimentary site study.

The repository would only be placed under NWMO owned land. The site-specific layout has not been determined, but based on land currently owned or optioned, as shown in Figure 7.17, the NWMO has identified that this area would be sufficient for the current used fuel projections (NWMO 2022), allowing for some expansion should that be agreed.

The placement rooms would be about 340 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^{o}C (Leupin et al. 2015). Containers will be placed in these rooms and surrounded by a clay-based buffer material to ensure low-permeability and chemically favorable conditions. The room ends would be sealed with bentonite clay and a concrete bulkhead plug.

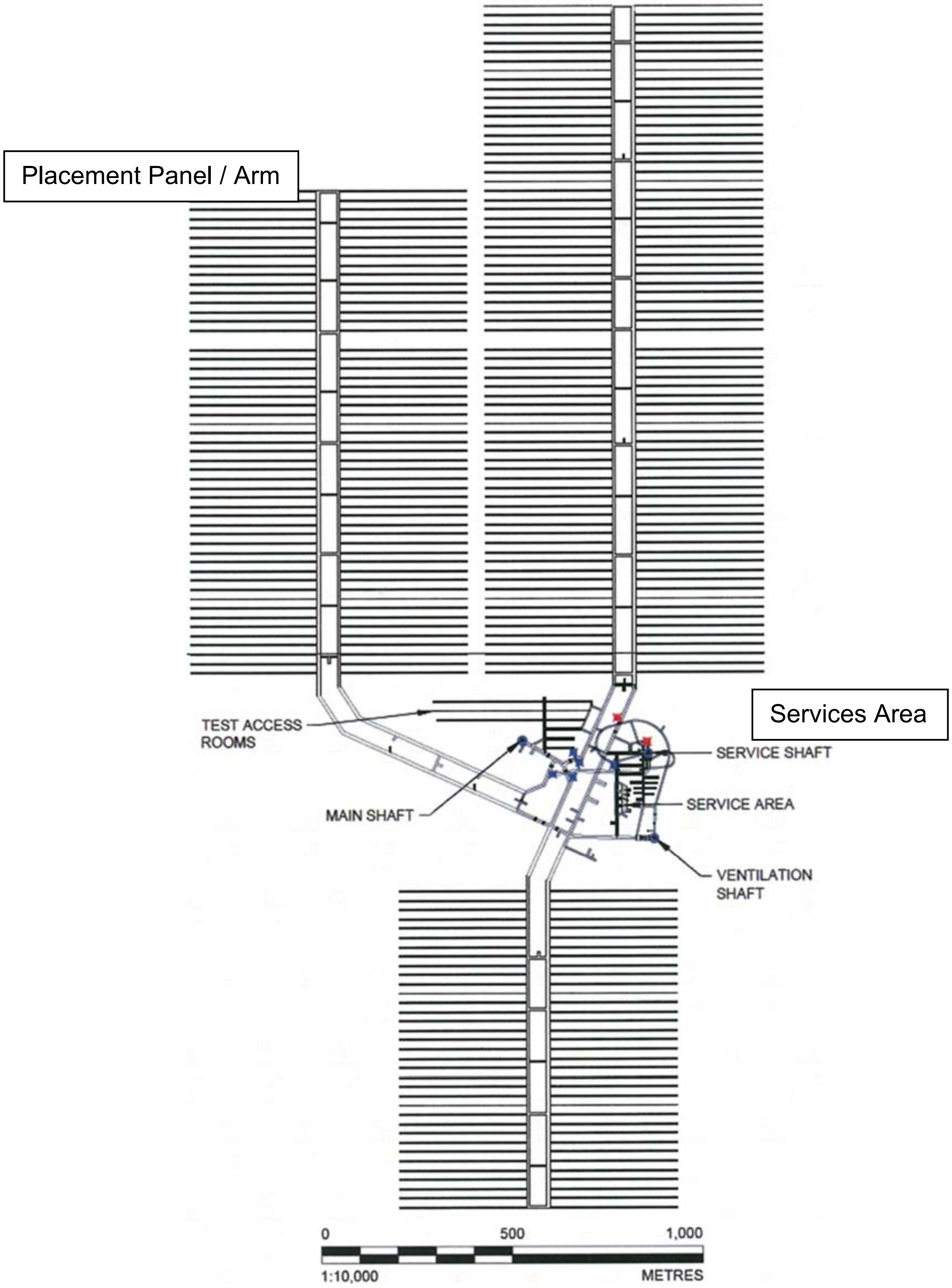

Figure 7.16: Conceptual underground repository layout for a hypothetical sedimentary rock site (NWMO 2018), showing central services area and illustrative positioning of placement panels to fit within the available area. Layout is for illustration purposes only and does not reflect the South Bruce Site.

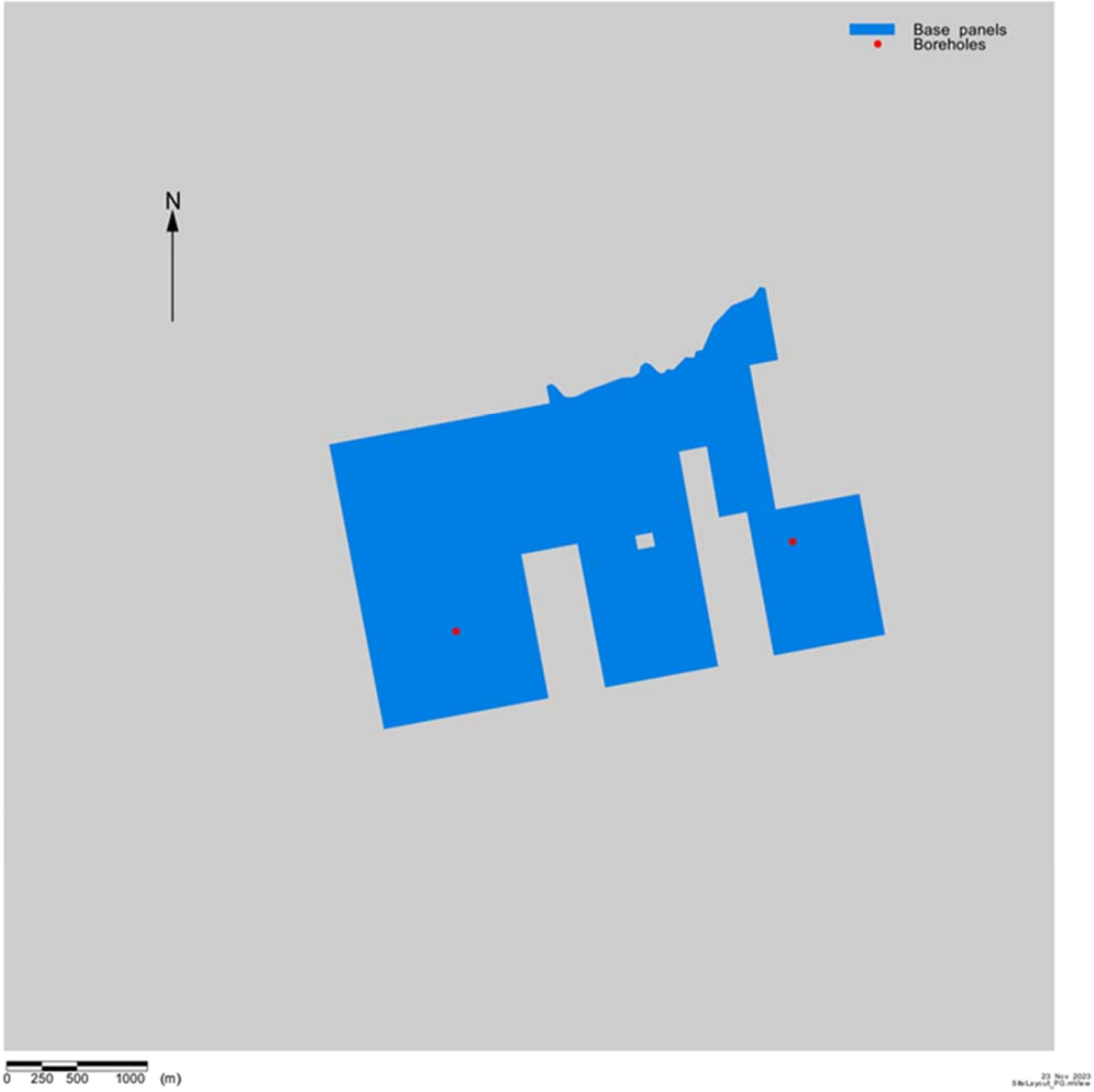

Figure 7.17: Potential underground area at South Bruce Site that could be used for placement rooms and central services area.

For the Cobourg Limestone rock at the South Bruce Site, excavation of the underground openings at around 650 m depth is not a technical problem. This rock formation is mechanically strong. There is much experience in this type of engineering in mines in Canada. There will likely be concrete floors, concrete bulkheads and local roof support, for example, rock bolts, grout, and/or shotcrete in the services area and access tunnels. Excavation techniques will be adopted that minimize the extent of the rock excavation damaged zone that typically forms around mined excavations.

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

7.2.4 Underground Ventilation

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

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

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

7.3 Surface Facilities

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

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

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

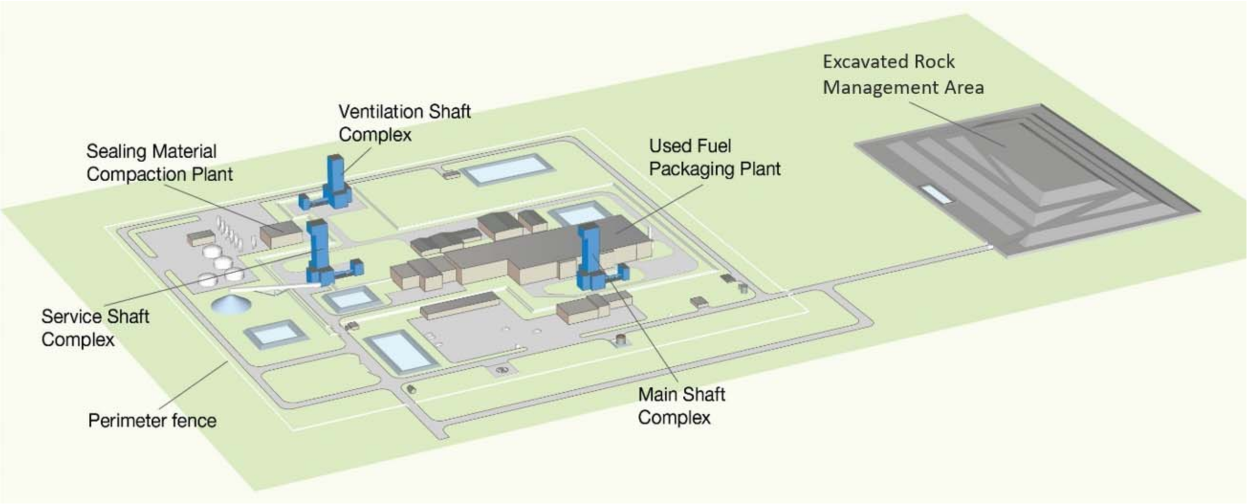

Figure 7.18: Illustration showing conceptual surface facility layout

7.3.1 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 of these component layers will further be connected to a back-up uninterrupted power supply, located within the Protected Area.

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

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

7.3.2 Used Fuel Packaging Plant

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

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

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

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

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

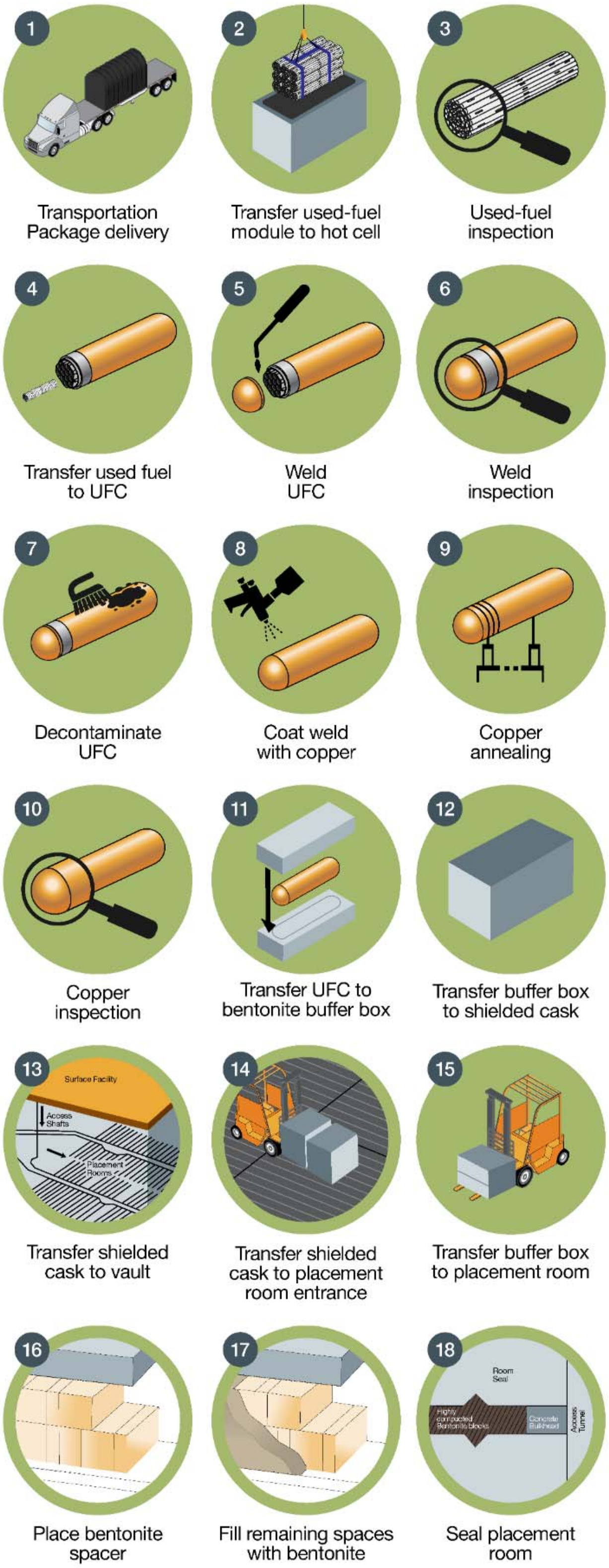

Figure 7.19: Illustration of the main steps with handling and emplacing the used fuel at the repository site.

7.4 Emissions and Waste Management

7.4.1 Water Management Systems

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

At the South Bruce Site, the current reference design assumes conservatively that both water and wastewater systems are independently sourced and located at the site. The water source has not been determined yet. It could be from a nearby surface water body (i.e., Teeswater River) or well. At the South Bruce Site, there may be a possibility to connect to the existing municipal water and wastewater sewage systems. These options will be further examined, should the South Bruce site be selected, through the detailed design phases and in discussions with the community.

If not connected to the existing wastewater sewage systems, sewage collected from all serviced buildings will be piped to an on-site sewage treatment plant for treatment to all applicable regulations prior to recycling or discharge to a local water body. Collected sludge will be taken for disposal off-site following all applicable regulations.

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

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

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

7.4.2 Excavated Rock Management Area

An Excavated Rock Management Area (ERMA) is a separate facility that will receive the excavated rock from underground construction over the life-cycle of the facility. The ERMA location will be within a 5 km distance of the repository shafts, and will be selected to minimize impact on streams and wetlands.

For a repository with a capacity of about 5.5 million fuel bundles (NWMO 2022), the rock pile with stormwater ditches would occupy an area of approximately ~700 m x 700 m with a rock pile height of 15 m. This is larger than previously estimated because it is based on a more accurate assessment of excavated rock, it includes the stormwater ditches around the rock pile, and it partially takes into account the land topography. The final design dimensions will be determined after the ERMA site has been identified.

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

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

PAG and salinity were tested throughout the sedimentary rock at the Bruce nuclear site. There is some limited evidence of PAG in some of the shales, however these volumes will be relatively small since they are limited to the shafts. There was also elevated chloride in leachate samples. Initial testing is underway with South Bruce rock; more would be undertaken as part of detailed site characterization.

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

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

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

7.4.3 Atmospheric Emissions

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

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

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

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

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

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

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

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

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

7.4.4 Active Solid and Liquid Wastes

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

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

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

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

7.4.5 Industrial Waste

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

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

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

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

7.5.1 Surface Area and Infrastructure

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

The area around the South Bruce Site is relatively flat and agricultural, as shown in Figure 1.1.

The land available to NWMO is outlined in Figure 1.2. Preliminary layouts have indicated that the site has sufficient surface area for the construction and operation of surface facilities and excavated rock management area. Currently, an on-site construction camp is not planned.

In terms of existing infrastructure, the proposed site is within 5 km of Teeswater and is approximately 10 km south of Ontario Highway 9. The Goderich-Exeter Railway (GEXR) rail line is approximately 50 km to the south. Electrical transmission and natural gas distribution are available in the region.

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

7.5.2 Natural Hazards

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

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

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

Given the site is located in southern Ontario, one hazard of note is the risk from high winds including possibility of tornado. Although the risk of direct impact by tornado is very low given the small surface facility size, this risk would be mitigated through design features such as the thick concrete walls in the Used Fuel Packaging Plan. Also, the used fuel placed underground would not be affected because of the protection of the overlying rock.

Another specific hazard is the risk of surface flooding under an extreme storm. This risk may be increased by climate change. A preliminary assessment of surface flooding hazard at the South Bruce site over the next century, including climate change, has indicated that there are areas within the site where flooding would not occur even under an extreme storm (Rodriguez and Brown 2022), due to the local topography. The detailed design would avoid this risk through surface facility location, grading, shaft collar height and stormwater management system.

7.5.3 Overburden

Geological mapping in the South Bruce Site area indicates that the bedrock is mostly covered by overburden deposits. Average overburden thickness is approximately 20 m and varies from 0 to 73 m within the Municipality of South Bruce. The thinnest overburden deposits are found in the valleys of the Teeswater River and Formosa Creek – the latter cuts down into limestone bedrock. Borehole 1 at the South Bruce Site encountered 19.6 m of overburden.

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 facilities.

7.5.4 Host Rock Strength and Bedrock Stresses

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

Based on the regional characteristics of the host rock, plus Canadian and international mining experience, there is high technical confidence that both the strength of the rock and bedrock stresses would allow the safe excavation, construction, operation, and closure of the deep geological repository.

7.5.5 Mitigating Repository-Induced Effects

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

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

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 this repository is located in an area that:

1. is amenable to the safe transportation of used nuclear fuel.
2. allows appropriate security and emergency response measures during operation and transportation of the used nuclear fuel.

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

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

8.1 Developing a Safe Transportation System

8.1.1 Transportation System Overview

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

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

8.1.2 Transportation Packages

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

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

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

The specific tests include:

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

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

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

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

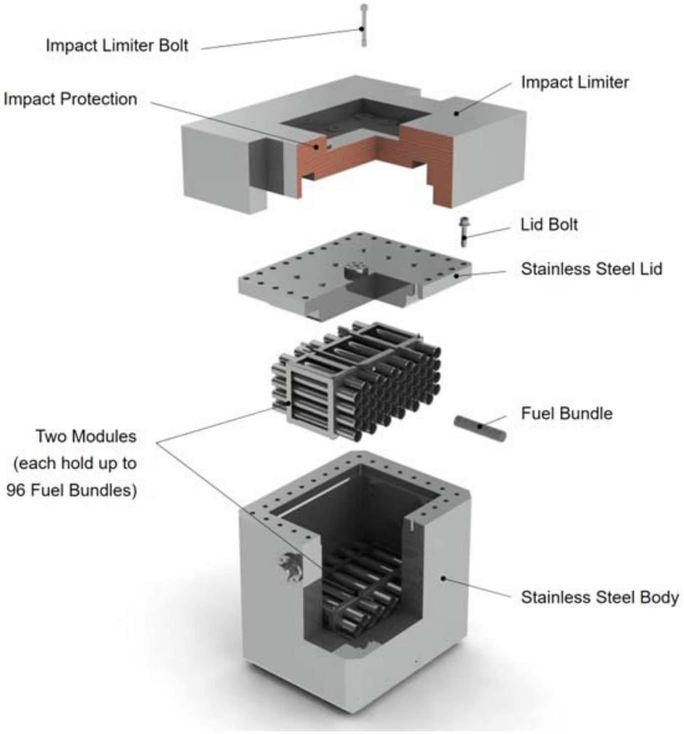

Figure 8.1: Illustration of Used Fuel Transportation Package (UFTP). It is a stainless-steel package with walls nearly 30 centimetres thick.

Table 8.1: Example Used Fuel Transportation Package Characteristics

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

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

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

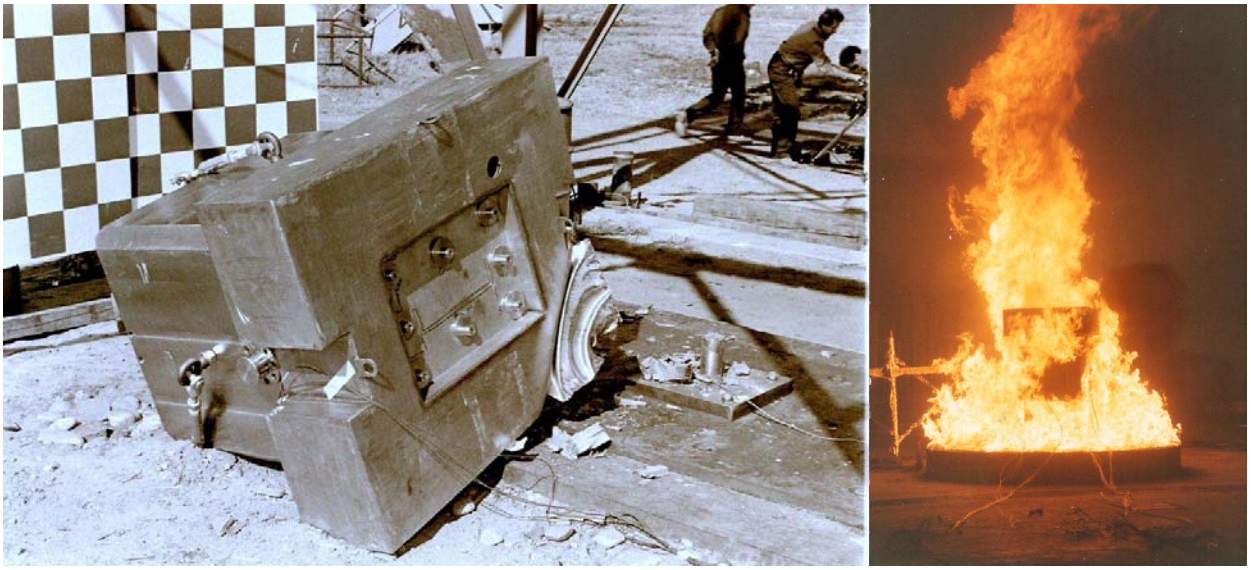

Figure 8.2: Half-Scale Used Fuel Transportation Package: (Left) after certification drop test; and (Right) during post-certification fire testing.

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

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

8.1.3 Transportation Modes

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

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

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

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

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

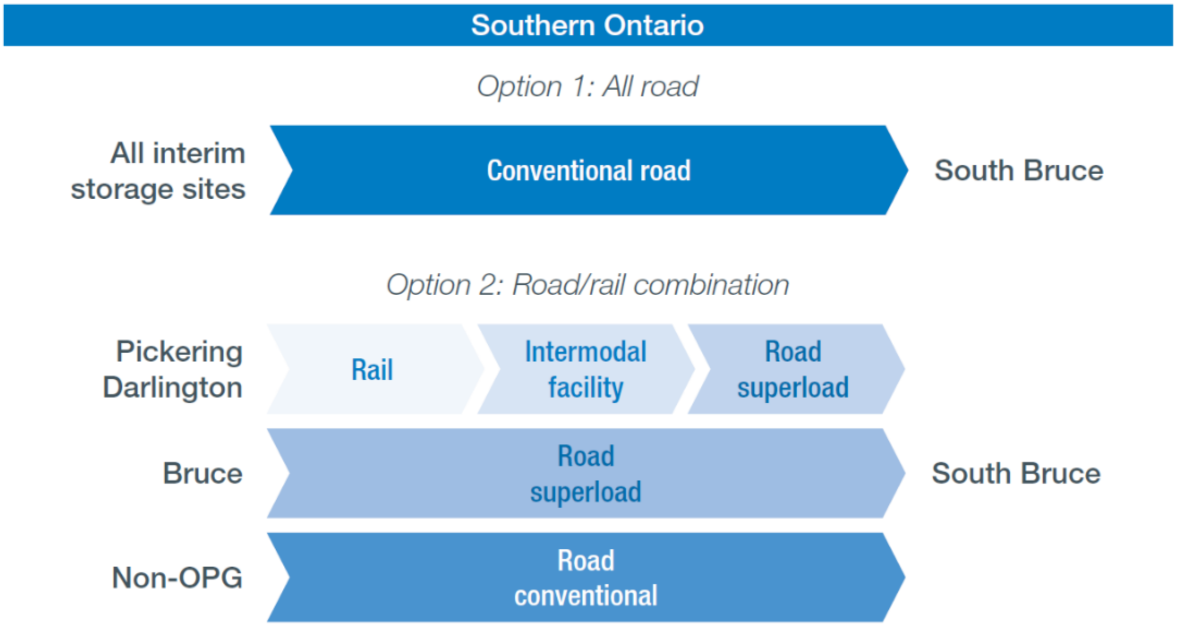

Figure 8.4: Transportation systems under consideration for the South Bruce Site

Conceptual designs of the all-road and road/rail systems were prepared for the South Bruce site and the technical feasibility of these systems assessed internally.

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

The South Bruce Site is located close to existing roads and highways such as Ontario Highway 9. However, the nearest rail line is the Goderich-Exeter Railway (GEXR) approximately 75 km by road to the south depending on the preferred routes.

For the road transportation system, some local road upgrades and/or development of new road connections from existing highway routes will be required. The NWMO and the Municipality of South Bruce are working with other regional communities to understand the changes that may need to be made to the road network and how the traffic to and from the site can be managed. Safety for all users - horse and buggy, bicycle, foot traffic, farm vehicle, cars and trucks - is being taken into consideration.

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

The NWMO considers both the road and road/rail transportation systems to be technically feasible for the South Bruce Site; however, the road/rail combination system requires more infrastructure, facilities, and package handling operations. At this time, the NWMO's reference

Used Fuel Transportation System for the South Bruce Site is the all-road system (NWMO 2021b). The all-road transportation system uses existing highway networks for the journey, provides more flexibility in terms of scheduling and routing, and avoids the need for intermodal facilities and superload shipments. Further assessment of the potential routes and infrastructure upgrade will be required after the site has been selected and detailed routing assessments have been completed.

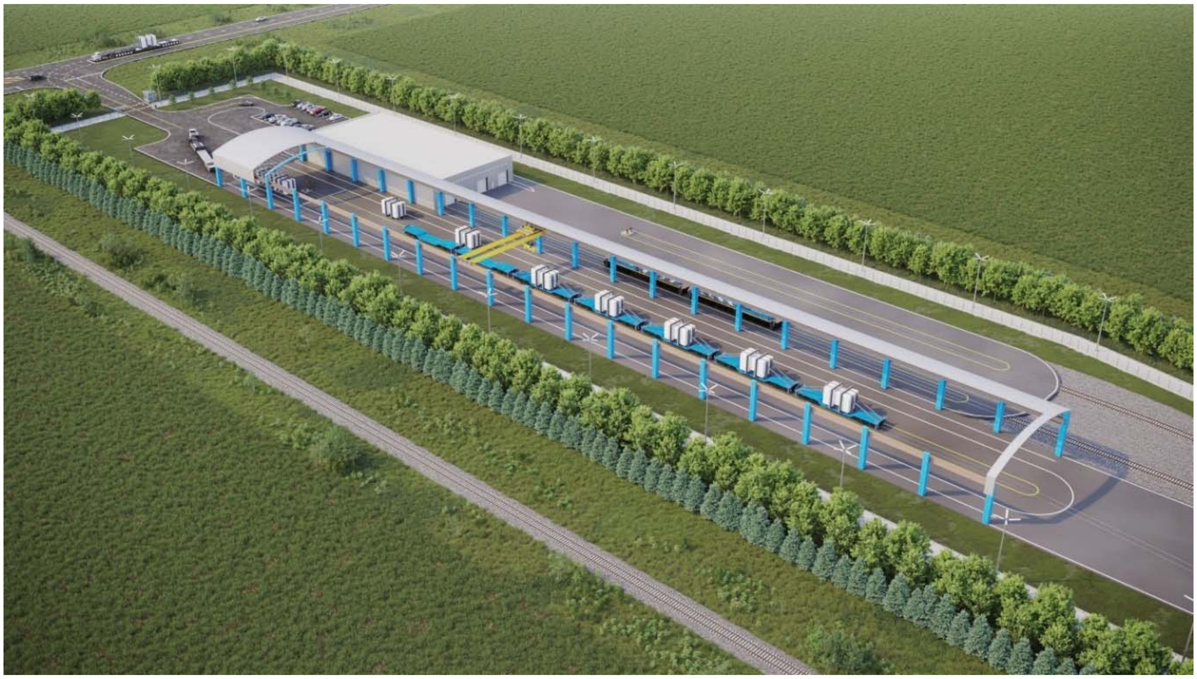

Figure 8.5: Conceptual Used Fuel Transportation System Intermodal Facility to transfer packages from rail to road modes.

8.2 Security and Emergency Response

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

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

Based on the information to date, the South Bruce Site location does not present any barriers that prevent effective security and emergency response planning and protocols for the operational phase. For example, in Bruce County, low and immediate level radioactive waste shipments have been occurring for 45 years in support of the Bruce nuclear site operations using such plans. Similar plans have been applied nationally and internationally on used fuel shipments successfully for over 50 years (US DOE 2016). As a result, there is high confidence that a safe and secure transportation system can be designed and operated.

8.2.1 Security

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

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

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

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

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

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

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

8.2.2 Emergency Response

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

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

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

- Description of the emergency response organization and external agencies, as well as their roles, responsibilities, capabilities, and duties, and how they will work together;
- Agreements on assistance with other facilities and/or other organizations;
- Plans for mobilizing and deploying resources for response;
- Description of the actions to be taken for potential incident scenarios, including who will complete them, and the specialized equipment that will be needed;
- Description of the technical advice that will be provided to responders over the phone and at the incident scene;
- 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 provinces immediate assistance to emergency response personnel in handling dangerous goods emergencies on a 24/7 basis. The emergency centre is staffed by bilingual scientists specializing in chemistry or a related field and trained in emergency response. CANUTEC would also have emergency contacts to initiate the shipment-based Transportation Emergency Response Plan which identifies technical advisors knowledgeable in response and recovery protocols who can support emergency management efforts.

9. NATURAL ANALOGUES FOR BARRIER DURABILITY

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

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

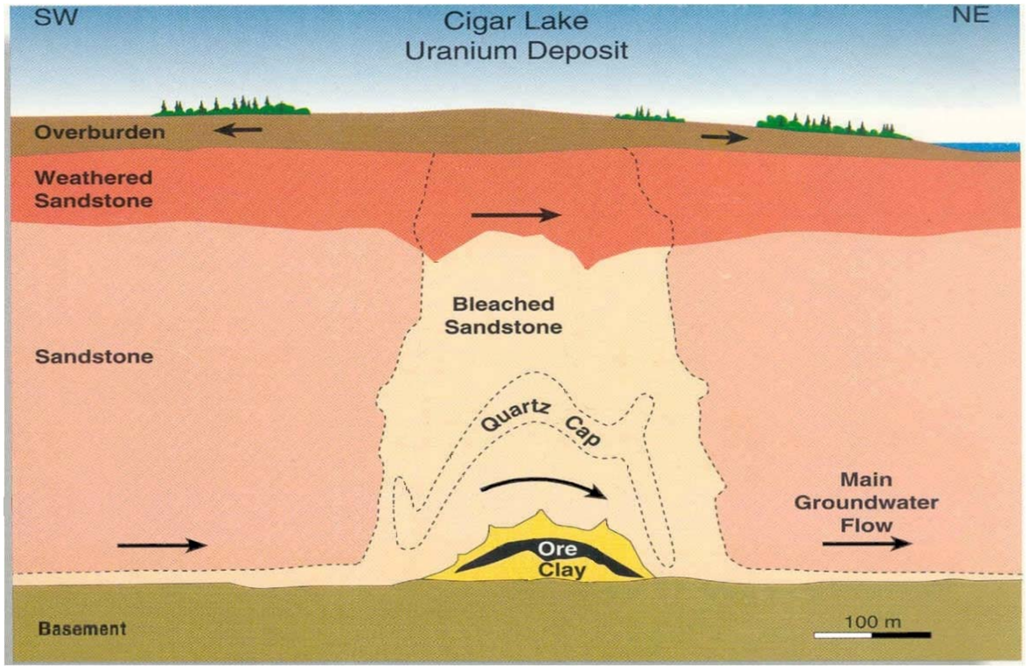

Figure 9.1: Cross-section of the Cigar Lake uranium ore body in Saskatchewan (adapted from Cramer and Smellie 1994). The uranium ore, surrounded by a clay layer at 430 m depth, has remained isolated from the surface environment for over 1.3 billion years.

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 ago 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 durability of copper in clays (SKB 2000).
Kronan cannon, Sweden	Bronze (copper alloy) cannon buried under sea mud for 300 years. Illustrates durability of copper under anoxic conditions.
Inchtuthill nails, Scotland	Buried iron nails from Romans. Illustrates slow iron corrosion in anoxic conditions.
Clay behaviour	
Wyoming bentonite, USA	Large deposits of bentonite clay formed from volcanic ash from 95 million years ago, illustrating durability of bentonite clay.
Dunnarobba forest, Italy	Wood tree stumps preserved in clay 2 million years ago. Illustrates ability of clay to preserve materials, in part through suppressing microbial activity.
Avonlea bentonite, Saskatchewan	Chemical and mineralogical stability of bentonite over 75 million years.
Cement and concrete behaviour	
Hadrian’s Wall, Great Britain	A simple form of cement was used in the walls 1900 years ago. Illustrates cement durability
Maqarin, Jordan	Interaction of 2-million-year-old natural cements with surrounding rock. Illustrates scientific understanding of the long-term effects is consistent with real site behaviour.

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

10. SAFETY ASSESSMENT

10.1 Context

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

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

Prior to the present evaluation of a repository on the South Bruce Site, seven post-closure safety assessment studies were carried out in Canada for hypothetical sites. Two of these assessments (AECL 1994; Wikjord et al. 1996) were reviewed as part of the federal 1998 Environmental Assessment on the concept of deep geological disposal of nuclear fuel waste, the Seaborn Panel (CEAA 1998). Subsequent generic assessments were conducted to develop and document understanding of the key factors in such safety cases. The most recent Canadian study for a sedimentary rock site was called the Seventh Case Study (NWMO 2018).

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

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

10.2 Assessment Basis

The assessment starts with the understanding of the used fuel itself, in terms of amounts and characteristics, including subcriticality. This is considered along with the information developed through the site characterization and environmental baseline programs, and the development of the engineering design for the site. This information is used in the safety assessment. A first summary of the radiological safety aspects of a repository in South Bruce was published as Arcadis (2023). As more information becomes available, and as part of the licensing process, the safety assessment is progressively iterated to provide a more detailed assessment.

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

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

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

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

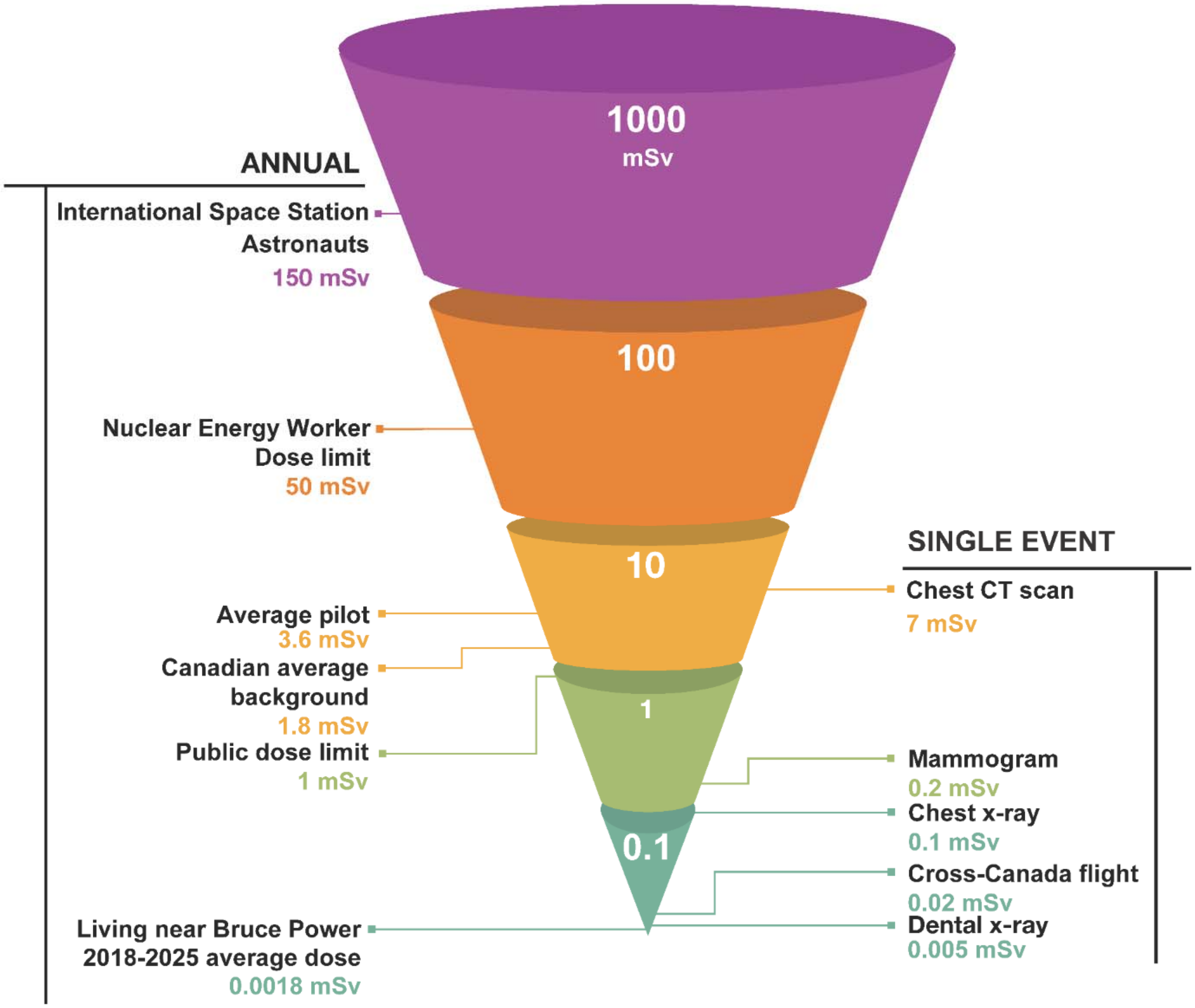

Figure 10.1: Typical radiation doses from various sources.

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

10.3 Pre-closure safety: Handling used nuclear fuel safely

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

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

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

10.3.1 Normal Operations

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

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

The assessment also considers more realistic lifestyles approximately representing people that might live near the facility to provide further insight into the repository safety.

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

10.3.2 Accidents

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

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

For each accident scenario,

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

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

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

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

10.3.3 Preliminary Results

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

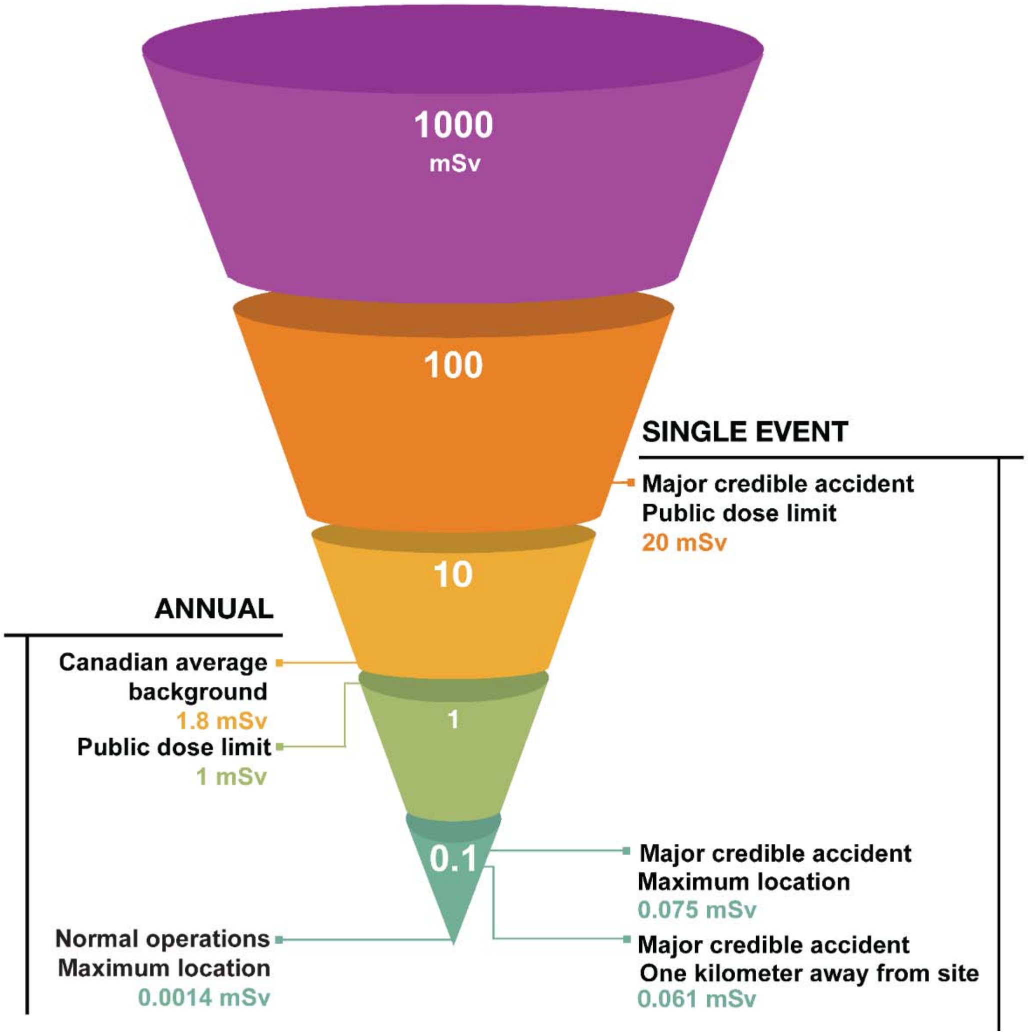

Figure 10.2: Illustration of potential pre-closure peak dose in comparison with natural background and regulatory limits.

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

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

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

The current preliminary assessment considers the underground repository is excavated at a depth of about 680 metres. The actual depth will be finalized based on more detailed site characterization.

10.4.1 Normal Evolution Scenarios

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

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

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

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

10.4.2 Alternative Scenarios

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

10.4.3 Preliminary Results

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

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

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

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

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

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

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

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

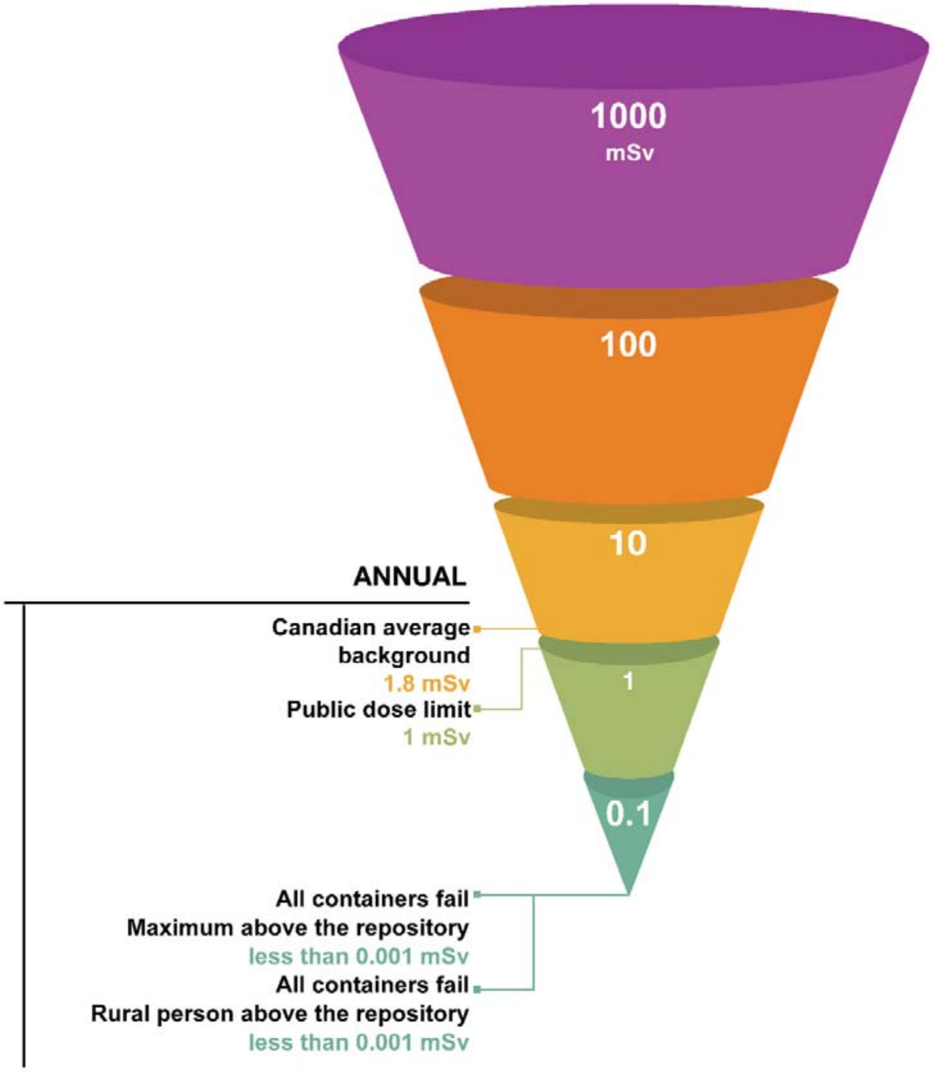

Figure 10.3: Illustration of potential post-closure peak dose in comparison with natural background and regulatory limits.

11. INTERNATIONAL CONSENSUS

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

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

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

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

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

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

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

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

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

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

COUNTRY	FORM OF WASTE	ROCK TYPE	DEPTH	CONTAINER CONCEPT	LOCATION	SCHEDULE
Finland	Used fuel	Crystalline rock (granite)	~450 m	Copper shell and cast iron structure; surrounded by bentonite clay	Olkiluoto site on southwest coast	Construction in progress. Operating licence application in 2021.
Sweden	Used fuel	Crystalline rock (granite)	470 m	Copper shell and cast iron structure; surrounded by bentonite clay	Forsmark site on east coast	Construction licence approval in 2022
France	Vitrified HLW, used fuel, long-lived ILW	Clay rock	~500 m	Steel containers; placed within concrete tunnels	Meuse/Haute-Marne area in east-central France	Construction licence application in 2023
Switzerland	Vitrified HLW and used fuel	Clay rock	400 – 1000 m	Steel canister (copper coating under evaluation) surrounded by bentonite clay	Nördlich Lägern area in northern Switzerland	Site selected in 2022
China	Vitrified HLW, used fuel	TBD	TBD	TBD	Three candidate sites in Gansu province	Constructing underground research lab at one site. Site selection in 2020s.
Russia	HLW	Crystalline rock	TBD	TBD	Zheleznogorsk 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.

12.1.1 Site Selection and Site Characterization Phase

At the South Bruce Site, instrumentation to monitor pressures will be installed in the first borehole, which will build on the 10 years of data obtained from similar instruments that had been installed in deep boreholes at the Bruce nuclear site. Five microseismic stations have been installed within a 50 km radius of the site, allowing for the ongoing monitoring of seismicity (i.e., earthquakes) down to magnitude one. In addition, a shallow groundwater monitoring network is being installed around the siting area and baseline environmental monitoring is underway. If this site is selected for detailed site characterization, additional monitoring installations would be completed at that time.

12.1.2 Site Preparation and Construction Phase

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

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

The tests during this phase will include short-term tests that would inform the application for a licence to operate the facility, as well as installation of longer-term tests that could be used to inform future closure decisions, such as installing sealing material compatibility tests in boreholes, or container tests in a trial placement room. Monitoring equipment would be installed as part of these tests located within the central services area.

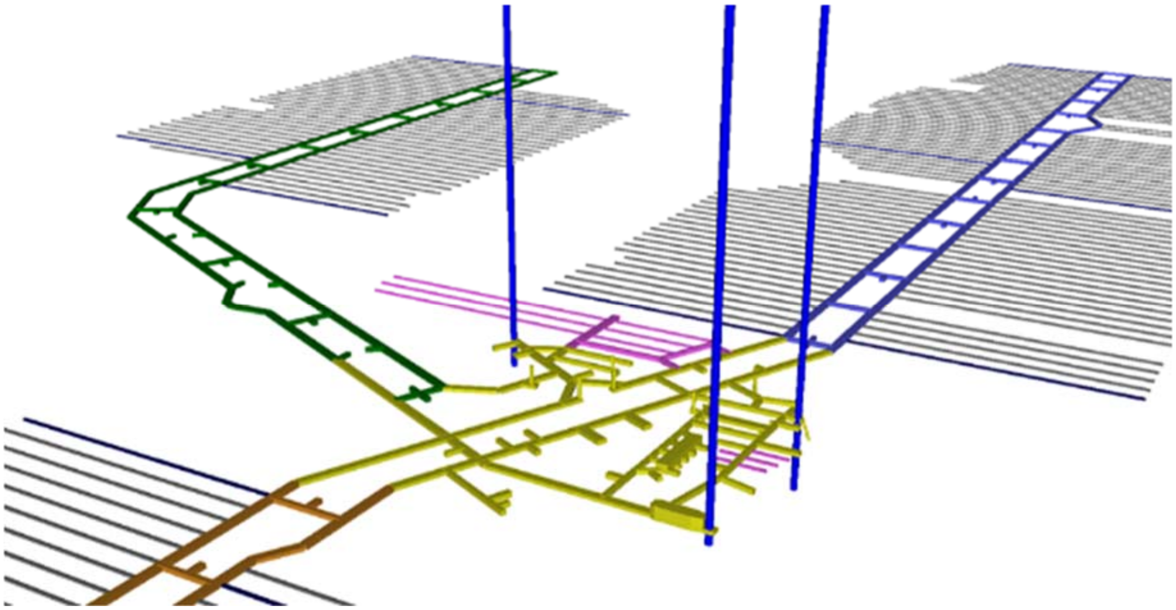

Figure 12.1: Illustration of centralized service area of repository showing the underground demonstration areas (highlighted in purple). (For illustration purposes only; does not reflect site-specific layout for South Bruce Site.)

12.1.3 Operations, Monitoring and Closure Phase

The operations, monitoring and closure phase will extend over a period of 100+ years. During this time, 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 underground 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 emission), tunnel monitoring (e.g., groundwater chemistry, temperature) and borehole monitoring (e.g., chemistry, radioactivity, porewater pressure, temperature). It will be used to verify that, at least at distances of tens of metres from the containers, conditions are as expected. All monitoring systems will be designed to ensure no impact to the functionality of the engineered barrier system and long-term safety of the repository.

The second category would include dedicated tests conducted within the UDF (or other niche areas). The first is the early UDF area where tests are installed soon after repository excavation has connected two shafts to allow an air flow and underground working area to be established. The second is a larger area for trial placement room tests.

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

The third category of monitoring covers specialty tests that may occur across the repository and check aspects of performance of the as-placed containers. Important factors in planning for this monitoring are the longevity of the sensors and whether they could affect the system that they are monitoring. Together, this puts an emphasis on monitoring that is remote, such that the instruments can be maintained if necessary and such that they do not interfere with the controlled conditions in the engineered barriers.

12.1.4 Post-closure Monitoring

After closure, the site is essentially fully returned to its intended end-state. The level of monitoring will be reduced but is expected to include continued environmental monitoring of surface and shallow groundwaters. Other monitoring that could be undertaken would focus on parameters that are indicative of the conditions near or within the repository. Options include monitoring through deep boreholes in the vicinity of the repository (e.g., groundwater chemistry, radionuclides, pressure, temperature), remote sensing such as acoustic emission or 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.

12.1.5 Knowledge Preservation

A related aspect to monitoring the repository, is preserving information on the repository over the long timescales required to, in part, prevent inadvertent intrusion, but also to keep future generations informed to support their planning and decisions. This is a topic of global interest, and Canada participates in these discussions (Pescatore et al. 2019).

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

13. REGULATORY FRAMEWORK

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

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

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

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

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

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

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

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

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

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

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

14. UNCERTAINTIES AND FUTURE WORK

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

One site-specific uncertainty is the nature of the Silurian-aged reef encountered beneath the eastern part of the South Bruce Site. While the 3D seismic survey was very useful in outlining the reef geometry, at least one additional borehole will be drilled into this feature to further understand it. Another site-specific uncertainty relates to the geometry of a sediment-filled valley located along the west side of the South Bruce Site, just west of the Teeswater River. The valley is about 50-m deep and trends southwesterly at surface. Both of these features are shallow relative to the proposed repository horizon in the Cobourg Formation, and neither is expected to impact the containment and isolation functions of the Ordovician rocks deeper beneath the site. However, both will need to be characterized to support repository design considerations, and to accurately model surface and shallow groundwater movement.

In addition, while the 3D seismic investigation has not identified any steeply dipping faults beneath the site, the presence or absence of such structures passing through the Ordovician rocks will continue to be investigated by inclined drilling. Ongoing microseismic monitoring will also help identify any active faults in the region.

To date, where the potential host rock has been encountered at depth, it has been tight (i.e., cannot 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 but also requires additional methods to understand the water chemistry deep in the subsurface. Given this limited availability of groundwater samples in the Cobourg Formation (and the overlying Ordovician shales), an emphasis is instead 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 results to date suggest that a hydrogeologically stable environment, with low rates of mass transport, is present at depth beneath the South Bruce Site. Additional information regarding an understanding of the relative ages of fluids within the shallow to deep groundwater systems, is still on-going to support these initial conclusions. Additional analyses also now need to be completed, based on the available site-specific geochemical information indicating a high salinity environment exists at the proposed repository depth, in order to allow assessments to be made of potential interactions with engineered barrier materials should the site be selected to host a repository.

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

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

Geosphere Model, and the past and projected future conditions (e.g., future ice ages) will be documented in a Geosynthesis report.

It should also be noted that the simple geometry and laterally continuous nature of the sedimentary formations suggest that the overall geological character of the bedrock beneath the South Bruce Site is already well understood, with uncertainty that is acceptable at this stage of the project.

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

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

The high salinity of the porewater at repository depth is an important feature of this site. It is generally favourable for repository performance as it is consistent with long-term geological stability and low groundwater flow. High salinity however has a range of effects on the engineered barriers that need to be considered. For example, it reduces the extent of bentonite clay swelling, but is favourable for suppressing microbial activity, which is one of the functions of the swelling clay. Work to date has been conducted using regional chemistry and salinity information. As the specific chemistry at this site is measured, work will be needed to establish properties and optimized design for these specific chemistry conditions.

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 geology and groundwater chemistry into the safety assessment. Preliminary results indicate that the facility will be safe, even under major accidents. However as a nuclear and industrial facility, appropriate emergency services will need to be in place within the facility and in the region. Early assessment has identified some of these needs, and also there is sufficient time to address them (DPRA 2022).

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

15. CONCLUSIONS

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

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

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

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

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

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

This report is part of a larger and ongoing site assessment process. Ongoing and future technical work will include further site studies, design development and safety analyses to further check and clarity 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 begin, there will be continued monitoring to ensure that the site is and remains suitable.

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APPENDIX A: List of Published Site-Specific Technical Reports

Report Number	Report Title
APM-REP-01332-0295	Phase 2 Initial Borehole Drilling and Testing, South Bruce. WP13 Technical Report: Ongoing Monitoring of Monitoring Wells SB_MW01-01, SB_MW01-02 and MECP1401064 During Drilling of SB_BH01 and SB_BH02
APM-REP-01332-0313	Phase 2 Initial Borehole Drilling and Testing, South Bruce. WP13: Technical Report for Monitoring Well (SB_MW01) Installation at SB_BH02
APM-REP-01332-0314	Phase 2 Initial Borehole Drilling and Testing, South Bruce. WP01A – Drill Site and Access Road Construction Report for SB_BH01
APM-REP-01332-0315	Phase 2 Initial Borehole Drilling and Testing, South Bruce. WP01B: Site Commissioning Report for SB_BH01
APM-REP-01332-0316	Phase 2 Initial Borehole Drilling and Testing – South Bruce. WP02: Data Report for Borehole Drilling and Coring at SB_BH01
APM-REP-01332-0319	Phase 2 Initial Borehole Drilling and Testing, South Bruce. WP04C Data Report: Porewater Extraction and Analyses, and Petrographic Analysis for SB_BH01
APM-REP-01332-0321	Phase 2 Initial Borehole Drilling and Testing, South Bruce. WP04G Data Report: Organic Geochemistry and Clay Mineralogy for SB_BH01
APM-REP-01332-0323	Phase 2 Initial Borehole Drilling and Testing, South Bruce. WP06: Hydraulic Testing Summary Report for SB_BH01
APM-REP-01332-0324	Phase 2 Initial Borehole Drilling and Testing, South Bruce. WP07 Data Report: Opportunistic Groundwater Sampling and Testing for SB_BH01
APM-REP-01332-0325	Phase 2 Initial Borehole Drilling and Testing, South Bruce. WP09 Data Report for Westbay MP55 Multi-Level Groundwater Monitoring System Installation at SB_BH01
APM-REP-01332-0326	Phase 2 Initial Borehole Drilling and Testing, South Bruce Area. WP10- Geological Integration Report for Borehole SB_BH01
APM-REP-01332-0327	Phase 2 Initial Borehole Drilling and Testing, South Bruce. WP01: Site Construction Report for SB_BH02.
APM-REP-01332-0328	Phase 2 Initial Borehole Drilling and Testing, South Bruce. WP01B: Site Commissioning Report for SB_BH02
APM-REP-01332-0329	Phase 2 Initial Borehole Drilling and Testing – South Bruce. WP02: Data Report for Borehole Drilling and Coring at SB_BH02
APM-REP-01332-0330	Phase 2 Initial Borehole Drilling and Testing, South Bruce. WP03 Data Report: Geological and Geotechnical Core Logging, Photography, and Sampling for SB_BH01
APM-REP-01332-0332	Phase 2 Initial Borehole Drilling and Testing, South Bruce. WP04C Data Report: Porewater Extraction and Analyses, and Petrographic Analysis for SB_BH02
APM-REP-01332-0334	Phase 2 Initial Borehole Drilling and Testing, South Bruce. WP04G Data Report: Organic Geochemistry and Clay Mineralogy for SB_BH02
APM-REP-01332-0335	Phase 2 Initial Borehole Drilling and Testing, South Bruce. WP03 Data Report: Geological and Geotechnical Core Logging, Photography and Sampling for SB_BH02
APM-REP-01332-0336	Phase 2 Initial Borehole Drilling and Testing, South Bruce. WP06: Hydraulic Testing Summary Report for SB_BH02
APM-REP-01332-0338	Phase 2 Initial Borehole Drilling and Testing, South Bruce. WP08 Data Report: Temporary Well Sealing for SB_BH02
APM-REP-01332-0339	Phase 2 Initial Borehole Drilling and Testing, South Bruce Area. WP10- Geological Integration Report for Borehole SB_ BH02
APM-REP-01332-0379	3D Geological Model for South Bruce and Surrounding Region: Model Version 1.0
APM-REP-01332-0381	South Bruce Area Microseismic Monitoring Project, Annual Event Summary Report, November 2021 - December 2022
APM-REP-01332-0424	Phase 2 Initial Borehole Drilling and Testing, South Bruce. WP01: Site Decommissioning Report for SB_BH01
APM-REP-01332-0425	Phase 2 Initial Borehole Drilling and Testing, South Bruce. WP01: Site Decommissioning Report for SB_BH02
APM-REP-01332-0426	Phase 2 Initial Borehole Drilling and Testing, South Bruce. Construction Noise and Vibration Study for SB_BH01 and SB_BH02 Sites
APM-REP-01332-0427	Phase 2 Initial Borehole Drilling and Testing, South Bruce. Air Quality Study for SB_BH01 and SB_BH02 Sites
APM-REP-01332-0428	Phase 2 Initial Borehole Drilling and Testing, South Bruce. Dust, Noise, and Vibration Background Study for SB_BH01 and SB_BH02 sites, in South Bruce
APM-REP-06144-0107	Phase 1 Desktop Assessment, Environment Report
APM-REP-06144-0108	Phase 1 Geoscientific Desktop Preliminary Assessment of Potential Suitability for Siting a Deep Geological Repository for Canada's Used Nuclear Fuel
APM-REP-06144-0109	Phase 1 Geoscientific Desktop Preliminary Assessment, Terrain and Remote Sensing Study
APM-REP-06144-0110	Phase 1 Geoscientific Desktop Preliminary Assessment, Processing and Interpretation of Borehole Geophysical Log and 2D Seismic Data
APM-REP-06144-0111	Phase 1 Geoscientific Desktop Preliminary Assessment, Processing and Interpretation of Geophysical Data
NWMO-TR-2019-20	Petroleum Assessment of the Huron Domain Area
NWMO-TR-2022-22	Seismic Activity in Southern Ontario: Annual Progress Report for the Period January 01 – December 31, 2020
NWMO-TR-2023-10	Sensitivity Analyses of Surface Boundary Conditions During Long-Term Climate Change