Nuclear Waste Management Organization

Preliminary Radiological Safety Study - South Bruce

August 2023

Preliminary Radiological Safety Study - South Bruce

August 2023

Prepared By:
Arcadis Canada Inc.
121 Granton Drive, Suite 12
Richmond Hill
Ontario L4B 3N4
Phone: 905 764 9380

Prepared For:
Nuclear Waste Management Organization
4th Floor, 22 St. Clair Avenue East
Toronto, ON
M4T 2S3

Our Ref:
30181492

Prepared by:

Ryan Kovacs, B.Sc.
Environmental Scientist

Frank Garisto

Frank Garisto, Ph.D.
Senior Technical Specialist, Nuclear Waste Management

Reviewed by:

Nava Garisto

Nava C. Garisto, Ph.D.
National Discipline Leader, Risk and Radioactivity

Iteration History

Iteration		Details of Iteration	Author	Reviewer
No.	Date			
R000	14 Aug 2023	Revision 0	Ryan Kovacs Frank Garisto	Nava Garisto

This study was prepared by Arcadis Canada Inc. referred to as Arcadis in this report. The Arcadis team that prepared this report includes:

- **Ryan Kovacs:** Environmental Scientist in Arcadis' Risk and Radioactivity group. Mr. Kovacs has over 10 years of experience covering a variety of technical and radiological projects. This includes licensing, risk assessments (e.g., Human Health & Ecological Risk Assessments), safety assessments, radiological exposure assessments, and spills risk assessments. Mr. Kovacs has an Honours B.Sc. in Biomedical Science from the University of Waterloo, as well as a Graduate Diploma in Environmental Assessment and Management from Niagara College. Mr. Kovacs is a member of the 2021 Canadian Standards Association (CSA) N288.6 technical sub-committee (TSC) on Environmental Risk Assessment and was a member of the original 2012 TSC. He was also a member of the CSA N288.7 TSC on groundwater monitoring and co-chaired the CSA N288.4 TSC on Environmental Monitoring.

- **Dr. Frank Garisto:** Senior Scientist and Safety Assessment Specialist with over 30 years of research and consulting experience related to radioactive waste and used nuclear fuel. Dr. Garisto has a Ph.D. in Chemistry from the University of Toronto. Frank has been actively involved in the preparation of safety assessment analyses and reports for several safety cases in Canada related to used nuclear fuel disposal, through AECL, OPG, and the NWMO. He was a technical contributor to AECL's study on Disposal of Canada's Nuclear Fuel (1987 – 1992), in particular, to the solubility and solubility-limited dissolution models. He was actively involved as a technical lead in Third Case Study, Fourth Case Study, Fifth Case Study, and Sixth Case Study Postclosure Safety Assessment studies of used nuclear fuel disposal in a deep geological repository, spanning 2002 to 2017. Dr. Garisto was a contributing author to the 4th and 5th Case Study's Data and Codes Reports and Postclosure Safety Assessment Reports. These safety assessments, safety cases, case studies and technical documents are related to determining and assessing the long-term safety of used nuclear fuel disposal.

- **Dr. Nava C. Garisto:** National Discipline Leader in Risk and Radioactivity at Arcadis with over 30 years of research and consulting experience related to radioactive waste management. Nava has a Ph.D. in Chemical Physics and is the author of over 100 journal publications and reports on nuclear waste, environmental assessments, risk assessments, and nuclear safety. Nava has a broad Canadian and international radioactivity experience across the nuclear fuel cycle, including uranium mines and mills (Elliot Lake, Saskatchewan and internationally), fuel fabrication and processing plants (e.g., Cameco's CFM, PHCF, BRR), nuclear generating stations (all Canadian stations) and decommissioning projects (e.g., CNL's NSDF and NPD Projects as well as WISMUT German sites). She is a member of N288 and N292

CSA nuclear committees and was a member of Environment Canada’s Expert Review group on the assessment of radionuclides in the environment and of the Canada-Sweden binational committee on nuclear fuel disposal; she was also a member of the Materials Research Society on the Scientific Basis of Nuclear Waste Disposal and has chaired an International Review Team on the safety assessment of nuclear waste disposal for the U.S. National Energy Institute.

The report has benefited from constructive comments from P. Gierszewski, K Glenn, C. Boyle, L. Morton, and M. Pahor.

Contents

Figures

Acronyms

AECL	Atomic Energy of Canada Limited
ALARA	As Low As Reasonably Achievable
BEIR	National Academy of Sciences, Biological Effects of Ionizing Radiation
CANDU	CANada Deuterium Uranium
CCTV	Closed-Circuit Television
CNSC	Canadian Nuclear Safety Commission
CSA	Canadian Standard Association
DGR	Deep Geological Repository
ECCC	Environment & Climate Change Canada
ERT	Emergency Response Team
IA	Impact Assessment
IAAC	Impact Assessment Agency of Canada
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
LNT	Linear No-Threshold
mSv	Millisievert, one thousandth of a sievert
NFWA	*Nuclear Fuel Waste Act*
NPP	Nuclear Power Plants
NSCA	*Nuclear Safety and Control Act*
NWMO	Nuclear Waste Management Organization
OPG	Ontario Power Generation
PostSA	Post-closure Safety Assessment
PreSA	Pre-closure Safety Assessment
QA/QC	Quality Assurance/Quality Control
RADICON	Radiation and Incidence of Cancer Around Ontario Nuclear Power Plants
SKB	Swedish Nuclear Fuel and Waste Management Company
SPIN	Safety and Performance Indicators
Sv	Sievert
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WIPP	Waste Isolation Pilot Plant (USA)
WHO	World Health Organization

Glossary

The following glossary of terms is adopted from NWMO (2021a) unless otherwise noted.

Alpha Particle – A positively charged particle ejected spontaneously from the nuclei of some radioactive elements. A group of radionuclides emitting alpha particles are measured as “gross alpha”, for example, U-235 and U-238. (Revised based on CNSC 2021a)

Analogue (Geosphere) – A geosphere environment, which may have properties relevant to present or future conditions expected at the deep geological repository site, that is used to improve the understanding of long-term geologic and hydrogeologic stability and to demonstrate concepts of long-term waste isolation and containment.

Analogue (Site Specific) – Site specific analogues are derived from the closest possible approximations (models developed to test hypotheses), and direct analogies against observations from the site. These analogues are used to study the long-term behaviour of features, events and processes observed, or caused by a repository, and to evaluate long-term site performance.

Atmospheric Radionuclide – radioactive nuclei produced by the interactions of cosmic rays with the nuclei of atmospheric constituents. The radionuclide most relevant to public exposure is carbon-14 (C-14, or ^{14}C). (Revised and simplified based on UNSCEAR 2010)

Backfill – A low-permeability clay-based or cement-based material manufactured and placed to fill the volume of the excavated openings in a geological repository.

Background Radiation – The dose or dose rate (or an observed measure related to the dose or dose rate) attributable to all sources other than the one specified, including natural background radiation and global fallout from nuclear weapons testing in this report. (Revised based on CNSC 2021a)

Baseline – Referring to radiation and radioactivity baseline, in the context of this report, refers to radiation and radioactivity that is already present in the area before the Project had begun. (Revised based on CNSC 2020b)

Becquerel – The unit of radioactivity (or activity), equal to one nucleus decay per second. (CNSC 2021a)

Bedrock – A general term for the rock, usually solid, that underlies soil or other unconsolidated, superficial material.

Beta Particle – A charged particle that is emitted from the nucleus of a radioactive element during radioactive decay of an unstable atom. A group of radionuclides emitting beta particles are measured as “gross beta”, for example, K-40 and Sr-90. (Revised based on CNSC 2021a)

Biosphere – The physical media (atmosphere, soil, surface waters and associated sediments) and the living organisms (including humans) that interact with them.

Borehole – A hole bored or drilled into rock.

Buffer – A low-permeable clay-based material placed to completely surround each used nuclear fuel container in a deep geological repository.

Buffer Box – A pair of highly compacted bentonite blocks that encase a completed Used Fuel Container. The loaded buffer box is eventually laid in the underground placement room.

CANDU – CANadian Deuterium Uranium. The term is often associated with the CANDU reactor, a heavy water reactor design invented and developed in Canada by Atomic Energy of Canada Limited (AECL), Ontario Power Generation (formerly the Hydro-electric Power Commission of Ontario) and GE Canada (formerly Canadian General Electric).

Closure – The administrative and technical actions directed at a repository at the end of its operating lifetime. For example, covering the waste (for a near surface repository), backfilling and/or sealing of rooms, tunnels and/or shafts (for a geological repository), and termination or completion of activities in any associated structures.

Contaminant – in the context of this report, refers to any radiological substance that has the potential to cause an undue effect. (Revised based on CSA Standard N288.6 (CSA 2012))

Critical Group – A group of people whose characteristics (such as habits, location or age) cause them to be representative of the more highly exposed individuals, receiving a higher dose than other groups in the exposed population (also referred to as Exposure Group).

Crystalline Rock – A rock of igneous or metamorphic origin consisting wholly of crystallized minerals.

Decommissioning – The administrative and technical actions taken to retire a facility from service or to cease licensed activities, and which allow the removal of some or all of the regulatory controls from a facility or location where nuclear substances are managed, possessed or stored. Decommissioning activities for nuclear facilities in Canada require a regulatory licence and are overseen by the Canadian Nuclear Safety Commission (CNSC).

Deep Geological Repository (or DGR, or Repository, or underground repository) – The underground portion of the deep geological repository facility.

Diffusion – The process by which substances dissolved in water move by random motion from areas of higher concentration to areas of lower concentration.

Dose – A measure of the energy deposited by radiation in a tissue. In this report, dose refers specifically to ‘effective dose’ unless specified otherwise. Effective dose accounts for different tissues’ sensitivity to different types of radiation. Dose is expressed in units of the Sievert (Sv) (and related millisieverts, microsieverts, etc.).

Dose Rate – Dose per unit time and measured, for example, in millisieverts per year (mSv/y). (Revised based on IAEA 2019)

Dry Storage Cask(s) – large portable steel and concrete container for surface storage of used nuclear fuel. The dry storage cask is the dry storage technology utilized by Ontario Power Generation.

Engineered Barrier – A physical obstruction that has been constructed to prevent or delay water seepage and/or radionuclide migration and/or migration of other materials between components in the repository, or between the repository and the surface environment.

Environment Media – The biotic and abiotic components of the environment. Also referred to as media or a medium. For example: soil, air, sediment, groundwater. (Adapted from CSA N288.6 (CSA 2012))

Fallout – Radioactive debris from an atmospheric nuclear test or nuclear accidents that has been deposited locally or globally through the atmosphere. (Revised based on UNSCEAR 2010)

Fault – A fracture or a zone of fractures that occurs as a result of brittle deformation and across which there is relative displacement parallel to the fracture surfaces.

Fuel Bundle (or Bundle) – A fuel bundle is an assembly of fuel elements welded to zirconium-end plates, in which each fuel element comprises a sealed, zirconium-alloy tube filled with ceramic, uranium-dioxide fuel pellets. The fuel bundle is deemed to be a *used* fuel bundle when it has undergone fission in a nuclear reactor (i.e., irradiated) and has been removed from a reactor. An intact used fuel bundle has no structural defects and no penetrations through the zirconium-alloy tubes. A defective used fuel-bundle has a penetration through the zirconium-alloy tube of one or more fuel elements. A damaged used fuel bundle has either one or more fuel elements disconnected from a zirconium-end plate, or one or more elements that are physically deformed or broken into two or more pieces.

Gamma Radiation – Penetrating electromagnetic radiation emitted from an atom’s nucleus. Also called gamma rays. (CNSC 2021a)

Geosphere – The rock around the repository and extending up to the biosphere. It can consist of both an unsaturated zone (which is above the groundwater table) and the saturated zone (which is below the groundwater table).

Glaciation – The formation, movement, advance and recession of glaciers or ice sheets.

Human Intrusion – Human actions that modify the performance of engineered and/or natural barriers, leading to the creation of a route by which humans (potentially both the intruder(s) and the public) could be exposed to radionuclides derived from the repository.

Institutional Control – Post-closure control of a deep geological repository site by an authority or institution, as designated under the laws of a country or state. This control may be active (monitoring, surveillance, remedial work) or passive (land use control).

Isotope – One or more species of a chemical element that have the same number of protons in the nucleus but a different number of neutrons, which results in small variations in the atomic mass. For example, oxygen has 8 protons, but the atomic masses of naturally occurring oxygen isotopes (^{16}O, ^{17}O and ^{18}O) vary because the number of neutrons within the respective atoms are different, at 8, 9 and 10, respectively.

Natural Radiation – The doses, dose rates or activity concentrations associated with natural sources, for example, cosmic radiation, radon. (Revised based on IAEA 2019)

Manufactured Radiation – Also called “anthropogenic” radiation, is generated by human activities such as nuclear power plants, medical equipment and nuclear weapons testing. (Revised and simplified based on IAEA 2019 and CNSC 2020a)

Multiple-Barrier Concept – A philosophy of providing two or more barriers to contain used nuclear fuel or other radioactive materials within and surrounding a deep geological repository, which prevent or inhibit migration of radionuclides and other contaminants from the waste form to the biosphere. This includes the engineered barriers (e.g., corrosion-resistant containers and sealing systems) and the natural barrier (e.g., the geosphere).

Module – A rack system carrying used nuclear fuel.

Pathway (also called Exposure Pathway) – A route by which contaminants can reach humans or biota and cause exposure. An exposure pathway may be very simple – for example, external exposure from airborne contaminants – or can involve a more complex chain of interactions – for example, internal exposure as a result of drinking milk from cows that ate contaminated grass.

Permeability (and Permeable) – A measure of the relative ease of fluid flow through a geologic medium. It is based on the physical characteristics of the medium such as porosity.

Placement Room – An underground opening in a deep geological repository that is designed and excavated specifically for the placement and isolation of containers of used nuclear fuel.

Post-closure (Phase) – The period of time following closure of the deep geological repository.

Pre-closure (Phase) – The period of time that includes all activities related to siting, construction and operations, as well as decommissioning and closure of all components of the deep geological repository.

Radiation – In the context of this report, refers to ionizing radiation, i.e., energy in the form of moving waves or streams of particles that are capable of producing ion pairs in biological materials. Examples include alpha particles, beta particles, gamma rays, X-rays, and neutrons. (CNSC 2020a)

Radioactive Decay – Also referred to as “decay” in this report, the process of spontaneous transformation of unstable atomic nuclei to a more stable atomic nuclei, accompanied by the emission of gamma rays, X-rays and/or subatomic particles. The resulting emission(s) is defined as radiation.

Radioactivity – The phenomenon whereby atoms undergo radioactive decay; also referring to “activity” in this report that measures an amount of radionuclide in a given energy state at a given time.

Radioisotope – A radioactive isotope.

Radionuclide – Atom with an unstable nucleus which can undergo radioactive decay.

Receptor – In the context of this particular report, a hypothetical human (adult, child, or infant) that is exposed to radiation.

Risk – A multi-attribute quantity expressing hazard, danger or chance of harmful or injurious consequences associated with actual or potential exposures. It relates to quantities such as the probability that specific deleterious consequences may arise and the magnitude and character of such consequences.

Sedimentary Rock – Rock originated by the deposition of sediment through transport and deposition by water, wind, or ice, and subsequently lithified.

Sievert (Sv) – The unit of effective dose, equal to joules per kilogram. Millisievert (mSv) are more commonly used, which represent a thousandth of a sievert. (Revised based on CNSC 2021a)

Surface Facilities – All surface structures, materials, processes, procedures and other aspects that support the safe operation of a deep geological repository facility. Their primary function is to receive used nuclear fuel shipped from interim storage facilities, repackage the used nuclear fuel bundles into durable, corrosion resistant used nuclear fuel containers, and transfer the containers underground for placement in the repository.

Transport Cask – A shielded container used to transport a loaded buffer box from the surface facilities to the underground placement room.

Used Fuel Container – The external barrier material (e.g., canister, coating and shielding materials, welds) that holds and contains the used nuclear fuel bundles *within the repository placement rooms*. It is a discrete unit that can be individually identified and handled at the repository facility.

Used Fuel Transportation Package – A re-useable transportation package designed for the safe shipment of fuel bundles stored in modules from source to destination.

Used Nuclear Fuel – Irradiated nuclear fuel removed from a commercial or research nuclear fission reactor.

Executive Summary

The Project

Nuclear energy has powered communities in Canada for decades. An unavoidable by-product of nuclear energy is used nuclear fuel. Used nuclear fuel gives off radiation and is a potential hazard to human health and the environment if not properly managed. While the hazard continues to diminish over time, for practical purposes, used nuclear fuel remains hazardous essentially indefinitely. All of Canada's used nuclear fuel is safely stored on an interim basis in facilities at or near the nuclear reactor sites where it is generated. Although the challenge of long-term management for Canada's used nuclear fuel has been studied for decades, there is currently no implemented solution. The Nuclear Waste Management Organization (NWMO) was established in 2002 by Canada's nuclear electricity corporations in accordance with the federal *Nuclear Fuel Waste Act* (*NFWA*) to study approaches for the management of nuclear fuel waste and recommend a preferred approach. In 2007, the Government of Canada selected an Adaptive Phased Management approach and gave NWMO the mandate to implement it. Canada's plan requires used nuclear fuel to be contained and isolated in a deep geological repository (DGR). It also calls for a comprehensive process to select a site with an informed and willing host community for the Project.

Siting

The NWMO has established a siting process, based on extensive public and Indigenous input. (NWMO 2021b). The NWMO is committed to proceeding with the Project in stages in an open, transparent, and inclusive manner. The site selection process has been underway since 2010. This process started with 22 municipalities and Indigenous communities that expressed interest. Over time the list has narrowed and today the NWMO is engaging with the two remaining potential siting areas: the Wabigoon Lake Ojibway Nation-Ignace area in northwestern Ontario, and the Saugeen Ojibway Nation-South Bruce area in southern Ontario (referred to as South Bruce in this report, for brevity).

Selection of a preferred site is expected to occur in 2024. Following this, the Project will undergo the Impact Assessment and initial Canadian Nuclear Safety Commission (CNSC) licensing processes, which are expected to conclude in 2029. The site preparation and construction phases are expected to require several years. Subsequent phases include an Operations Phase which involves the receipt, handling, and placement of used nuclear fuel in the DGR, followed by decommissioning of surface facilities and site closure.

Community Studies

NWMO is preparing a series of community studies to provide information to South Bruce residents, stakeholders and rights-holders. This report is one of them. The purpose of this particular community study is to summarize how safety would be ensured and how radiological effects to members of the public would be minimized so that they stay below relevant regulatory criteria and do not cause any undue health effects. This report is based on information available by December 2022.

The report focuses on the operations phase and the post-closure phase because these are the main phases that involve radioactivity.

i. Radiation, Radioactivity and its Presence:

This section of the report briefly explains what radiation and radioactivity are, and what a 'dose' is. It also outlines the fact that there is natural background radiation around us always and everywhere, not just near nuclear facilities.

ii. Regulation of Radiation in Canada:

This section of the report briefly outlines how radiation and related projects are regulated in Canada. It notes the main agencies involved and which aspects they cover.

iii. Overview of the Project:

The complete lifecycle of the Project involves the following phases:

Site Selection Process

The NWMO began the site selection process in 2010. Technical assessments were conducted, along with engagement activities, to narrow the list of potential sites and focus on those with the strongest potential to meet the Project's criteria and where communities continue to be interested in exploring the Project. Once the site selection assessments are finished, a preferred site, with informed and willing host communities, will be selected and undergo more detailed characterization. Site selection is expected to be completed in 2024.

Site Preparation Phase

The site preparation phase includes activities such as clearing existing vegetation from planned building footprints, grading the site, fencing off the site, and installing initial utilities and infrastructure. Initial utilities and infrastructure include electricity, stormwater management systems, clean water and sewage systems, and fuel tanks, though some of these may be temporary setups at this phase. *It is important to understand that the site preparation phase does not involve the presence of used nuclear fuel on site.*

Construction Phase

The construction phase includes building the surface facilities as well as the underground repository. For planning purposes, the NWMO has assumed the construction phase could require about 10 years. *It is important to understand that the construction phase does not involve the presence of used nuclear fuel on site.*

Operations Phase

The operations phase includes the main process of receiving shipments of used nuclear fuel in Used Fuel Transportation Packages, repackaging the used nuclear fuel into Used Fuel Containers at the site, transferring them into the underground facility and emplacing them in the underground repository. Repackaging would take place in the Used Fuel Packaging Plant at the site.

Extended Monitoring Phase

Once all Used Fuel Containers have been emplaced in the repository, the NWMO would continue to monitor the long-term safety and performance of the repository for an extended period of time. The extended monitoring phase could last several decades; 70 years has been assumed for planning purposes. The actual duration of this phase would be informed by discussion with the regulator and with input from the communities.

Decommissioning and Closure Phase

Decommissioning activities for surface facilities would begin after enough monitoring data have been collected to support the decision to decommission and close the repository. Once complete, the repository would be closed and sealed, at which point the site will be graded and landscaped based on the end-state land use agreed with the communities. It is anticipated that permanent markers would be installed to inform future generations of the presence of the sealed repository. For planning purposes, the NWMO has assumed the decommissioning and closure phase would require about 25 years.

Post-closure Phase (Long Term)

The repository is designed to be passively safe after closure, with no need for human intervention and maintenance. The careful site selection work early in the Project will also help ensure that the facility will perform as planned for a long period of time. Post-closure monitoring would be in place for as long as needed in order to verify that the repository is behaving in a safe manner.

iv. Operations Phase:

During operations, used fuel is received at the site and transferred from the shipping packages to the underground packages, which are then placed underground. 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 radioactivity is contained within the fuel bundles. Therefore, the potential sources of radioactivity or radiation within the facility are the direct gamma and neutron radiation from the fuel bundles, and small amounts of gas or particulates that may be released from fuel during handling.

Fuel handling accidents within the facility would be very unlikely. Partly as the fuel handling is a simple transfer process. Also, the fuel is generating a small amount of decay heat, but not enough to cause an overheating accident, so it does not require water cooling. Both the transportation packages and the used fuel containers are very robust and able to withstand accidents. The facility itself will be robust, in part due to the thick walls used for shielding purposes.

Potential releases would be contained within the Used Fuel Packaging Plant through the following mitigation measures:

- Thick concrete and/or metal walls in the fuel handling areas, that provide gamma and neutron shielding.
- Fuel handling systems designed to minimize stress on fuel bundles, and to have them placed within sealed Used Fuel Containers as quickly as possible, to minimize releases.
- Air ventilation system, where air is directed inwards to the higher radioactivity areas, and then filtered and monitored before release through building stack.
- Dry decontamination and cleanup methods for clearing most surfaces.
- Process water treatment system, where any water used for washing or decontamination is cleaned, filtered and monitored before recycling or release.
- Monitoring equipment and shutdown capability.

An operational safety assessment is prepared by the NWMO that considers the design and safety features of the DGR, the potential releases, and the potential pathways by which people may be exposed to these releases. This ***Pre-closure Safety Assessment*** (PreSA) will assess public exposures based on the estimated emissions and compare them to regulatory criteria to ensure that there is no health risk to the public.

The PreSA will follow the approach outlined in Canadian standards, guidelines, and CNSC regulatory documents. A preliminary safety assessment is underway based on current site and design information, with some results to be complete by the end of 2023. The NWMO will update the assessment as the site and design details improve. And the design in turn will be modified as needed to address priorities identified in the preliminary safety assessment. Ultimately, this assessment will be independently reviewed by the CNSC as part of the licencing process.

v. Post-closure Phase:

The primary safety objective of a deep geological repository is the long-term containment and isolation of used nuclear fuel. The safety of the repository is based on a combination of the geology, properties of the waste, the engineering design, careful operations, and quality assurance processes including review and monitoring.

The purpose of the ***Post-closure Safety Assessment*** (PostSA) is to determine the potential effects of the repository on the health and safety of people and the environment in the long term, during the post-closure phase. The assessment timeframe is one million years, based on the time needed for the radioactivity of the used nuclear fuel to decay to essentially the same level as that in an equivalent amount of natural uranium.

The results presented in this report are largely based on NWMO's 2018 PostSA of used nuclear fuel disposal in sedimentary rock, and on NWMO's 2022 *Confidence in Safety Report*, reflecting the current understanding of the long term safety of the repository. Following the approach outlined in Canadian standards, guidelines, and applicable CNSC regulatory documents, the PostSA looks at normal evolution scenarios as well as hypothetical disruptive scenarios such as all containers failing, repository seals failing and undetected fault close to the DGR. Details are provided in NWMO (2018a).

The PostSA shows that corresponding radiological criteria are met with substantial safety margins during the post-closure phase. This result is consistent with previous assessments of a deep geological repository in Canada, as well as with safety assessment studies by other international radioactive waste management organizations.

Similar to the PreSA, the PostSA is being refined as the engineering design is improved. It is also refined to reflect increased understanding of the geology at the site based on on-going site-characterization work.

vi. Ensuring Safety:

Operations Phase

Ensuring safety during the operations phase focuses on preventing and minimizing releases and exposures. The following are ways in which the Project would ensure safety during the operations phase:

- Engineering, Design and Process Controls, to reduce exposures and releases.
- Emission Controls, to reduce and control the radionuclides in airborne and waterborne releases.
- Monitoring Systems and Monitoring Programs, to monitor the levels of radionuclides in releases and in the environment to verify that controls are performing as intended.
- Health & Safety Program, to uphold safety for workers and any members of the public visiting the site.

- Radiation Protection Program, to monitor and minimize the doses received by workers.
- Regular Maintenance, to reduce the likelihood of malfunctions and failures of facilities and equipment.
- Controlled Site Access, to prevent unintended or unauthorized access to the site.
- Emergency Preparedness – to mitigate the effects were an accident or malfunction to occur.
- Thorough Assessment before operations begin.
- Independent Third Party Monitoring, in addition to NWMO's environmental monitoring efforts.

Post-closure Phase

Ensuring safety during the post-closure phase relies mainly on proper siting, design and implementation of emplacement processes. Monitoring also plays an important role. The following are ways in which the Project would ensure safety during the post-closure phase:

- Implementing a multiple-barrier concept;
- Stability of the host rock;
- Isolation of deep water from the surface;
- Favourable underground chemical conditions for containment;
- Evidence gained from natural analogues;
- Depth of the repository reduces likelihood of intrusion;
- Confidence gained from similar international projects;
- Several Safety Assessment Case Studies;
- Using proven technologies;
- Radionuclide decay over time;
- Using monitoring programs to confirm performance.

In Summary:

This Community Study report provides information on and discusses the following topics:

- **Radiation, Radioactivity, and its Presence:** This report explains radiation, radioactivity, and dose. It also gives perspective on dose by offering specific examples.
- **Regulation of Radiation in Canada:** This report lists the main agencies related to the oversight of radiation and gives details on how the primary regulator (the CNSC) regulates projects.
- **Overview of the Project:** This report summarizes the main phases of the Project, with brief descriptions of the activities in each phase.
- **Operations and Post-closure Phases:** This report provides information on the potential radiological emissions from the Project on the health of members of the public.
- **Ensuring Safety:** This report summarizes several ways in which the Project would ensure safety during the operations phase and post-closure phase.

1 Introduction

1.1 Background

Who/What is the NWMO?

The Nuclear Waste Management Organization (NWMO) is responsible for designing and implementing Canada's plan for the safe, long-term management of used nuclear fuel. The plan requires used nuclear fuel to be contained and isolated in a deep geological repository (DGR). The plan also calls for a comprehensive process to select a site for the project with informed and willing host communities. The NWMO is a not-for-profit organization established in 2002 by Canada's nuclear electricity producers in accordance with the *Nuclear Fuel Waste Act* (*NFWA*).

Why is the NWMO's Project Needed?

For decades, Canadians have been using electricity generated by CANada Deuterium Uranium (CANDU) nuclear power reactors in Ontario, Quebec and New Brunswick. When CANDU fuel is removed from the reactor at the end of its useful life (referred to as used nuclear fuel), it is considered a waste product. Used nuclear fuel is highly radioactive and highly toxic. Although the initial radioactivity level of used nuclear fuel decreases rapidly with time, residual radioactivity (together with some chemical toxicity) persists, and the used nuclear fuel remains highly radioactive and potentially highly dangerous to humans and the environment for a very long period of time. Thus, used nuclear fuel requires very careful management, essentially indefinitely. For this reason and others, a passive, safe used nuclear fuel disposal system that contains and isolates the used nuclear fuel from the environment, in a deep geological repository (DGR), has become the preferred management option (Figure 1-1). This approach is inherently sustainable in that it is designed to protect future generations by not burdening them with the responsibility to manage wastes generated in the past and at present.

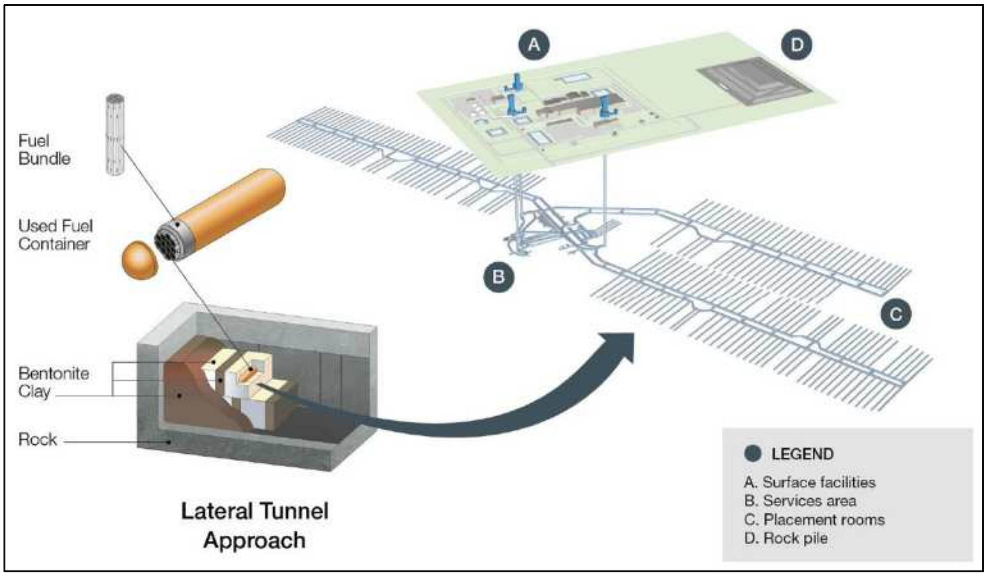


Figure 1-1 DGR Concept (NWMO 2021d)

What is the NWMO's Project?

The concept was developed through a dialogue with Canadians to reflect features considered important by citizens. It is consistent with nuclear waste management programs that have been developed in other countries, such as Sweden, the United Kingdom, Finland and France. As a plan for the future, the project charts a course for the safe, secure long-term management of used nuclear fuel, in line with best international practice and the expectations of Canadians.

The NWMO developed the site selection process, in collaboration with Canadians and Indigenous peoples, in order to ensure that the site that is ultimately selected for the DGR is safe and secure and meets the highest scientific, professional, and ethical standards. Currently, two sites remain in the selection process as a potential host community for the Project: (1) the Saugeen Ojibway Nation-South Bruce area, located in the Municipality of South Bruce near Teeswater, Ontario (referred to as South Bruce in this report, for brevity); and (2) the Wabigoon Lake Ojibway Nation-Ignace area in northwestern Ontario. The NWMO's aim is to select a single preferred site by the end of 2024.

What are the Community Studies?

The NWMO is preparing a series of Community Studies to provide information to South Bruce residents, stakeholders and rights-holders, on health and environmental aspects of the Project. Similar studies are being prepared for the site in the Wabigoon Lake Ojibway Nation-Ignace area. The study presented in this report is one of the Community Studies. The objectives of this study are outlined below.

Note to Reader

This and other community studies are preliminary and strategic in nature, all intended to identify possible consequences (e.g., to vulnerable populations, to local business opportunities and for local and regional job creation) in the Municipality of South Bruce, and other local and regional communities. Using information about the APM Project known at this point in time, these community studies will describe a range of possible consequences that are the subject of specific and separate studies. For each possible consequence, potential options and strategies will be offered to leverage opportunities and/or mitigate possible negative consequences/effects.

It is important to note that these community studies (developed collaboratively by NWMO and the Township of South Bruce) being investigated at this time are not the formal or final baseline or effects studies that will be part of the Impact Assessment as conducted under the regulatory process for the APM Project governed by the Impact Assessment Agreement of Canada. Effects assessment will be undertaken at a later date following the conclusion of the siting process, and the initiation of the formal regulatory process. Community studies will ultimately inform the APM Project hosting agreement between the NWMO and the Municipality of South Bruce. As well, they will potentially provide pertinent information for other regional agreements. The study will:

a) Explore in more detail the questions, aspirations and topics of interest expressed by the community through the Municipality of South Bruce project visioning process;
b) Assist the NWMO and the Municipality of South Bruce in developing and identifying possible programs and commitments that ensure the Project will be implemented in a manner that fosters the well-being of the Municipality of South Bruce and communities in the region;
c) Advance learning and understanding on topics of interest to communities in the Municipality of South Bruce and the region; and,
d) Provide the community with information it has requested to help them make an informed decision in the case of the Municipality of South Bruce and continue to inform dialogue with communities in the area and region prior to the conclusion of the site selection process in 2023.

The NWMO is committed to working collaboratively to ensure questions, concerns, and aspirations are captured and addressed through continuous engagement and dialogue.

The NWMO will independently engage with Saugeen Ojibway Nation and other Indigenous communities to understand how they wish to evaluate the potential negative effects and benefits that the Project may bring to their communities.

1.2 Objectives of this Community Study

The objectives of this particular Community Study, *Preliminary Radiological Safety Study – South Bruce*, are to provide information on:

- Potential radiological effects of the Project, during all its phases, on the safety of the residents of South Bruce and on future residents in the proximity of the site; and,
- A high-level description of safety features of the facility, mitigation and/or follow-up measures that could be taken if an increase in risk is identified during any phase of the project.

An additional objective is to provide important context and background information on:

- Radiation, radioactivity and their presence in the environment (in general);
- Relevant Canadian regulations pertaining to protection of people from radiation; and,
- Emissions of radioactivity potentially associated with the Project.

1.3 Report Scope

This report focusses on radiological aspects of the Project and their potential influence on the health of members of the public. Indigenous receptors are not in the scope of the present report. Non-radiological aspects, risk from transportation of used nuclear fuel to the site, and characterization of the South Bruce radiological baseline will be addressed in other NWMO documents.

This current report does not provide an estimate of the radiological effects of the Project on workers. Worker health and safety is addressed by developing and implementing a Health and Safety Program (see Section 7.1.4) and a Radiation Protection Program (see Section 7.1.5). There will be no radiation doses to workers during the site preparation and construction phases of the Project. A worker dose assessment for the operations phase will be prepared in the future, prior to construction of the site. Radiological dose to workers in the Canadian nuclear industry is discussed in Section 2.4.

This report summarizes and puts into context information available as of December 2022. It largely draws on the Confidence in Safety Report (NWMO 2022).

This study - *Preliminary Radiological Safety Study – South Bruce* - is relevant to guiding principle #1, established with the Municipality of South Bruce (MSB 2020):

- #1: The NWMO must demonstrate to the satisfaction of the Municipality that the Project will be subject to the highest standards of safety across its lifespan of construction, operation and into the distant future. This report presents international and Canadian standards of safety that the Project is expected to meet.

2 Radiation, Radioactivity, and Their Presence

2.1 What is Radiation?

Radiation plays a key role in many aspects of modern life, including the use of nuclear medicine, electricity generation and even space exploration.

The International Atomic Energy Agency (IAEA) defines radioactivity as the “the phenomenon whereby atoms undergo spontaneous random disintegration, usually accompanied by the emission of radiation” (IAEA 2019). By emitting radiation, radioactive elements go from one energy state to another, which eventually will result in an element no longer being radioactive. The radioactive decay process can take from less than a second, to billions of years depending on the radioactive element involved. As these unstable elements decay, they release energy and often become different elements. Radioactive materials are present in soil, rocks, air, water, and in people’s bodies. There is also artificial radiation from various sources, such as nuclear medicine (which uses radioactive material to diagnose and treat cancer), the nuclear fuel cycle, as well as commercial products like smoke detectors (CNSC 2020a).

Radiation can be described as energy in the form of moving waves or streams of particles. There are two types of radiation: non-ionizing and ionizing (Figure 2-1). Non-ionizing radiation does not possess enough energy to create charged atoms or molecules, called ions. Examples of non-ionizing radiation include radio waves and microwaves. Ionizing radiation, on the other hand, does possess sufficient energy to interact with matter, including the human body, and to create ions. Ions can be harmful to the human body, but ionizing radiation can also be used for many beneficial purposes (e.g., medical diagnosis using X-rays). Examples of ionizing radiation include alpha particles, gamma rays, X-rays and neutrons.

This study focusses on ionizing radiation.

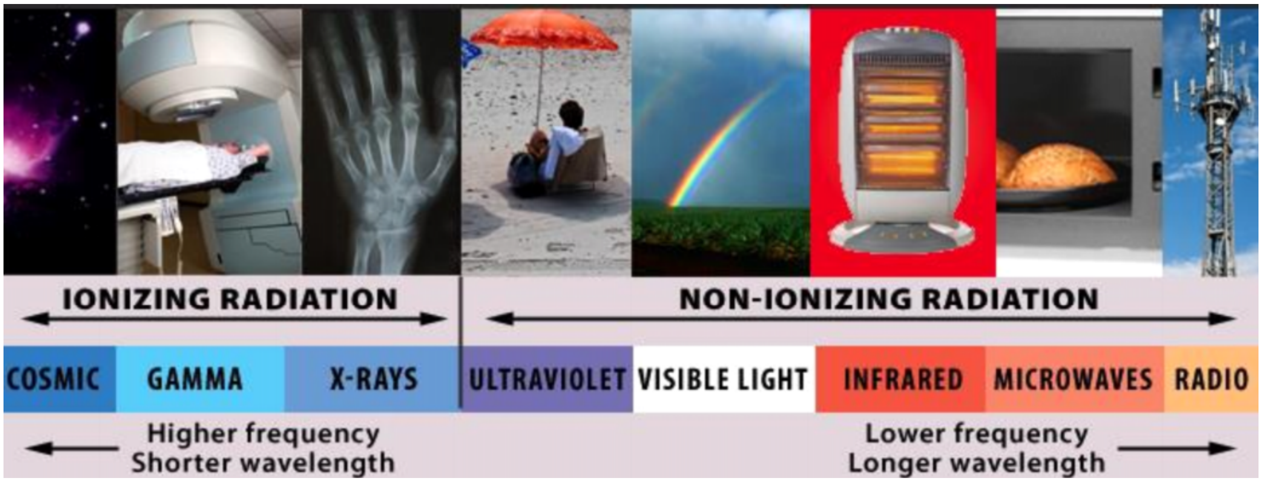


Figure 2-1 The Electromagnetic Spectrum and Examples (CNSC 2020a)

2.2 Isotope, Radioactivity and Half-life

An atom is the smallest unit of ordinary matter that forms a chemical element. Every atom is composed of a nucleus and one or more electrons bound to the nucleus (Figure 2-2 (a)). The nucleus is made of one or more protons and some number of neutrons. It is the number of protons in the nucleus (the atomic number) that distinguishes each element (Figure 2-2 (b)). The number of protons is unique to each element.

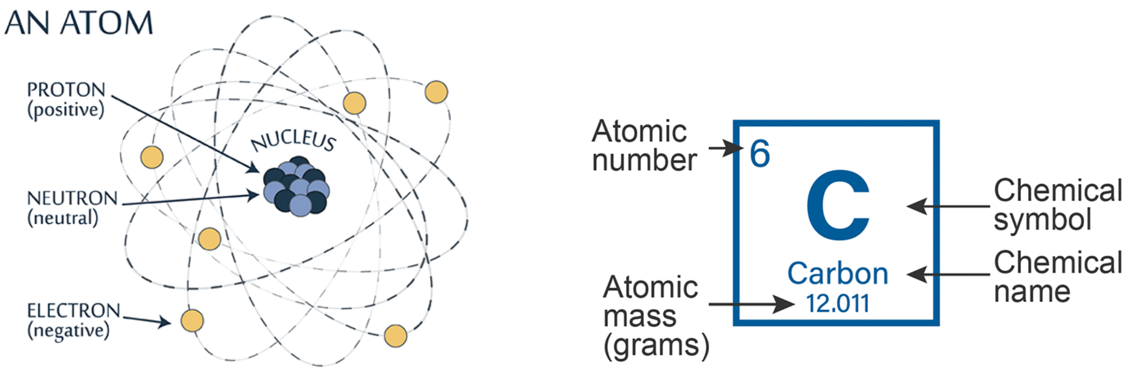


Figure 2-2 (a) An Illustrative Structure of An Atom (left) and (b) Symbols of An Element (right) (CNSC 2019a)

Nuclides of an element that have the same number of protons but not the same number of neutrons are called isotopes of that element. They are a variant of a basic element. Isotopes are typically written as "Element (chemical name or the symbol)-Atomic Mass" or "$^{\text{Atomic Mass}}$Element Symbol" to distinguish between them. The atomic mass is the sum of the number of protons and the number of neutrons in the nucleus.

For example, there are three isotopes of hydrogen, as shown in Figure 2-3: hydrogen-1 (one proton and no neutrons), hydrogen-2 or deuterium (one proton and one neutron), and hydrogen-3 which is called tritium (one proton and two neutrons). Another example is that both uranium-235 and uranium-238 are isotopes of uranium: uranium-235 has 92 protons and 143 neutrons, and uranium-238 has 92 protons and 146 neutrons. Uranium-235 can be written as Uranium-235, U-235, or ^{235}U.

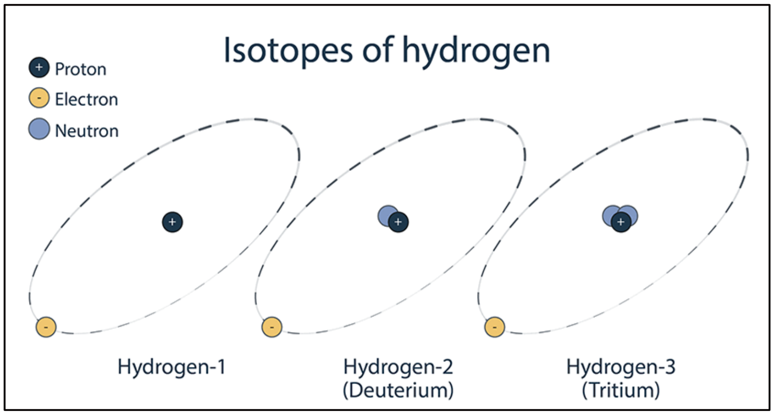


Figure 2-3 Isotopes of Hydrogen (CNSC 2019a)

Some isotopes are stable because the number of neutrons and protons in the nucleus is balanced, such as carbon-12 (6 protons and 6 neutrons) and oxygen-16 (8 protons and 8 neutrons). Some isotopes are unstable when there is a significant imbalance between the number of neutrons and protons in a nucleus; they may undergo a transformation in order to achieve stability. When the transformation happens, the atom decreases its mass by various means and gives off excess energy. This spontaneous process is known as radioactive decay and the particles and energy emitted in the disintegration are referred to as ionizing radiation. These unstable isotopes are also known as radioisotopes or radionuclides. The activity (or radioactivity) is expressed or measured in a unit called the becquerel (Bq). One Bq equals one disintegration per second. The higher the activity, the more radioactive the isotope is.

The half-life of a radioisotope is the time it takes for the radioactivity (of a given mass of radioisotope) to decay to half of its starting radioactivity. Each radioisotope has a unique half-life, which can be a fraction of a second, billions of years or some value in between. For example, iodine-131 has a half-life of eight days, while plutonium-239 has a half-life of 24,000 years. The decay is exponential, as illustrated in Figure 2-4 below; and, every half-life, the amount of iodine-131 decreases by a half.

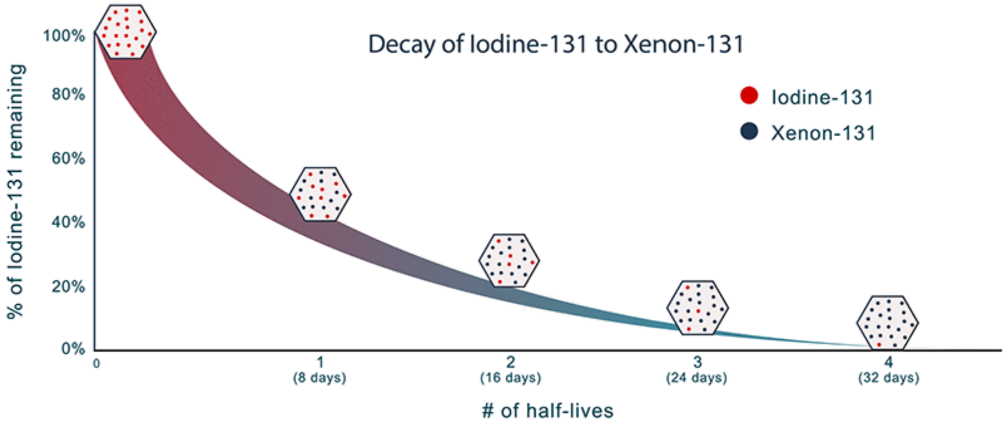


Figure 2-4 Illustration of Radioactive Decay and Half-life (CNSC 2019a)

2.3 Sources of Radiation

We live on a planet where we are exposed to natural background radiation. Radiation is present in soil, rocks, the air we breathe, the water we drink, and even in our own bodies. These sources of natural radiation make up the bulk of the total radiation we are exposed to every day.

We are also exposed to manufactured radiation from various sources, such as medical scans, X-rays, cancer treatments, the nuclear fuel cycle, as well as commercial products like smoke detectors (CNSC 2020a).

The following paragraphs describe the sources of natural and manufactured radiation to which people are typically exposed. For context, a study by Grasty and Lamarre (2004) found that the average dose that a Canadian receives from natural background sources is approximately 1.8 millisieverts (mSv) per year.

Cosmic Radiation

The earth's outer atmosphere is continually bombarded by cosmic rays, typically originating from the sun and other celestial events in the universe. Some ionizing radiation will penetrate the earth's atmosphere and become absorbed by humans, resulting in natural radiation exposure (CNSC 2020c).

The earth's atmosphere provides some shielding against this radiation. As a result, at sea level, cosmic radiation contributes about 10% of the total dose rate from natural radiation to which human beings have always been exposed. However, at higher altitudes in the atmosphere or in space, cosmic rays constitute the dominant radiation dose (UNSCEAR 2010).

Cosmic rays interact with the nuclei of atmospheric constituents and the interactions produce a number of radioactive nuclei. The most relevant of which to public exposure is carbon-14 (C-14, or ^{14}C). It arises from the interaction of slow cosmic neutrons with nitrogen-14 (N-14) in the earth atmosphere. Transformed into $^{14}CO_2$, it is used by plants for photosynthesis.

For context, the annual effective dose of radiation from cosmic rays in Vancouver, British Columbia, which is at sea level, is about 0.30 mSv (CNSC 2020c). Regions at higher altitudes receive more cosmic radiation (CNSC 2020c).

Terrestrial Radiation

The earth's crust is a major source of natural radiation, which is sometimes simply referred to as naturally occurring radiation. The main contributors are natural deposits of uranium, potassium and thorium which, in the process of natural radioactive decay, will release small amounts of ionizing radiation (CNSC 2020c). Only those radionuclides with half-lives comparable to the age of the earth, and their decay products, exist in sufficient quantity to contribute significantly to human population exposure (UNSCEAR 2010). For most people, their primary exposure to this radiation is from gamma-emitting radionuclides present in trace amounts in the soil, mainly potassium-40 (K-40), uranium-238 (U-238) and thorium-232 (Th-232). World-wide average concentrations in soil range from less than 300 Bq/kg to 3,000 Bq/kg for K-40, from 10 Bq/kg to 300 Bq/kg for U-238 and from less than 10 Bq/kg to 1,000 Bq/kg for Th-232.

People may also receive external exposures from building materials where traces of these naturally occurring elements are found. Thus, exposure to natural radiation can occur indoors as well as outdoors.

For context, in Canada, the estimated highest annual dose from terrestrial radiation is approximately 1.4 mSv, as measured in the Northwest Territories (CNSC 2020c).

Food and Drinking Water

Trace amounts of radioactive atoms are naturally found in food and drinking water. For instance, vegetables are cultivated in soil and irrigated with groundwater. Soil and water contain minerals and other elements, which in turn contain trace amounts of natural radionuclides. Once ingested with the vegetables, these radionuclides can result in internal exposure to natural radiation. Some of the essential elements that make up the human body, mainly potassium and carbon, have radioactive isotopes that add to our background radiation dose (CNSC 2020c).

For context, CNSC (2020c) mentions that several sources of natural radiation affect our bodies through the food we eat, the air we breathe and the water we drink, with Potassium-40 (K-40) being the main source of internal irradiation (aside from radon decay) found in a variety of everyday foods. The average effective dose from these sources is approximately 0.3 mSv a year (CNSC 2020c).

Airborne Radiation

Most of the exposure to natural radiation results from inhalation of radioactive gases, such as radon, that are produced by radioactive minerals found in soil and bedrock. Radon is an odourless and colourless radioactive gas that is produced by the decay of U-238. It is an inert gas, meaning that it does not react with surrounding matter. Because radon does not react, it can readily move up through the ground and into the atmosphere. Radon levels vary considerably by location depending on the composition of soil and bedrock (CNSC 2020c).

Once released into the air, these gases will normally dilute and decay to harmless levels in the atmosphere, but sometimes they are released from the soil into basements, and accumulate inside well-sealed buildings where they can be inhaled by occupants. On average, radon is the largest source of natural radiation exposure in Canada (CNSC 2020c).

For context, the average internal public dose from inhalation of natural radon is about 1 mSv/a, but the dose varies greatly with the geological composition of the environment. For example, the average dose from radon in Vancouver is 0.2 mSv/a, but in Winnipeg it is 2.2 mSv/a (NWMO, 2020).

Nuclear Weapon Testing and Global Fallout

Testing of nuclear weapons in the atmosphere was the most significant cause of exposure of the world population to manufactured environmental sources of radiation (UNSCEAR 2000). The practice continued from 1945 to 1980. The periods of most active testing were 1952–1958 and 1961–1962. After 1963, nuclear tests were mostly carried out underground (UNSCEAR 2010). Radioactive debris from an atmospheric nuclear test can be deposited locally or globally through the atmosphere, and named “local fallout” and “global fallout”, respectively. There have been no nuclear weapon tests conducted in Canada and therefore only global fallout applies.

Most of the radioactive material from nuclear weapon tests that went into the atmosphere has now been deposited. Many different radionuclides are formed in a nuclear explosion, but most decay rapidly, so that after an initial short period during which they contribute external radiation, they do not present a hazard to people or living things. In the long term, only three radionuclides, carbon-14, strontium-90 and cesium-137 give doses, doing so internally through dietary pathways (AECB 1995).

In addition to nuclear weapon testing, nuclear accidents such as the Chernobyl and the Fukushima nuclear accidents resulted in local and global fallout. Health Canada monitors atmospheric activity following such accidents. Further information on Health Canada's Radiation Surveillance Division, and the Canadian Radionuclide Monitoring Program, can be found online at Health Canada’s website.

Releases from Nuclear Power Generating Stations

The nuclear fuel cycle (e.g., uranium mines and mills, and nuclear power reactors), military establishments, research organizations, hospitals and non-nuclear industries all contribute to releases of radionuclides to the environment (IAEA 2004). Most of the manufactured radioactivity currently entering the environment is from the nuclear power industry. Air, soil, water and vegetables around Canadian nuclear generating stations are monitored by the electrical utilities, as well as independently by the Canadian Nuclear Safety Commission (CNSC) and by provincial authorities (CNSC 2020d). Further information on the CNSC's independent environmental monitoring program – including monitoring results – can be found on the CNSC's website. Publicly available information on monitoring performed at nuclear generating stations can typically be found on the operators' websites.

Other Sources

Other sources include:

- use of consumer products (e.g., cigarette smoke, smoke detectors and cathode-ray-tube type colour televisions and computer monitors);
- waste from human activities concentrating and/or releasing naturally occurring radionuclides (e.g., coal power plants, abstraction of oil and gas, smelting metals, manufacturing of fertilizer and building materials); and
- medical procedures involving exposure (e.g., diagnostics and radiotherapy).

Note that exposure from medical procedures is not typically included in estimates of public exposure; however, this study presents the typical doses from medical procedures for perspective.

2.4 Dose from Radiation

Effective dose is a general term that refers to the amount of energy absorbed by tissue from ionizing radiation. Effective dose is measured in sieverts (Sv) and is more commonly expressed in units of millisieverts (mSv), which represents one thousandth ($x10^{-3}$) of a sievert (CNSC 2020c).

The figure below (Figure 2-5) illustrates doses typically received by Canadians from a variety of sources, including medical procedures (dose per scan), natural background (annual dose), and living and working near nuclear power plants (annual dose). Annual dose limits, set by the CNSC, are also shown.

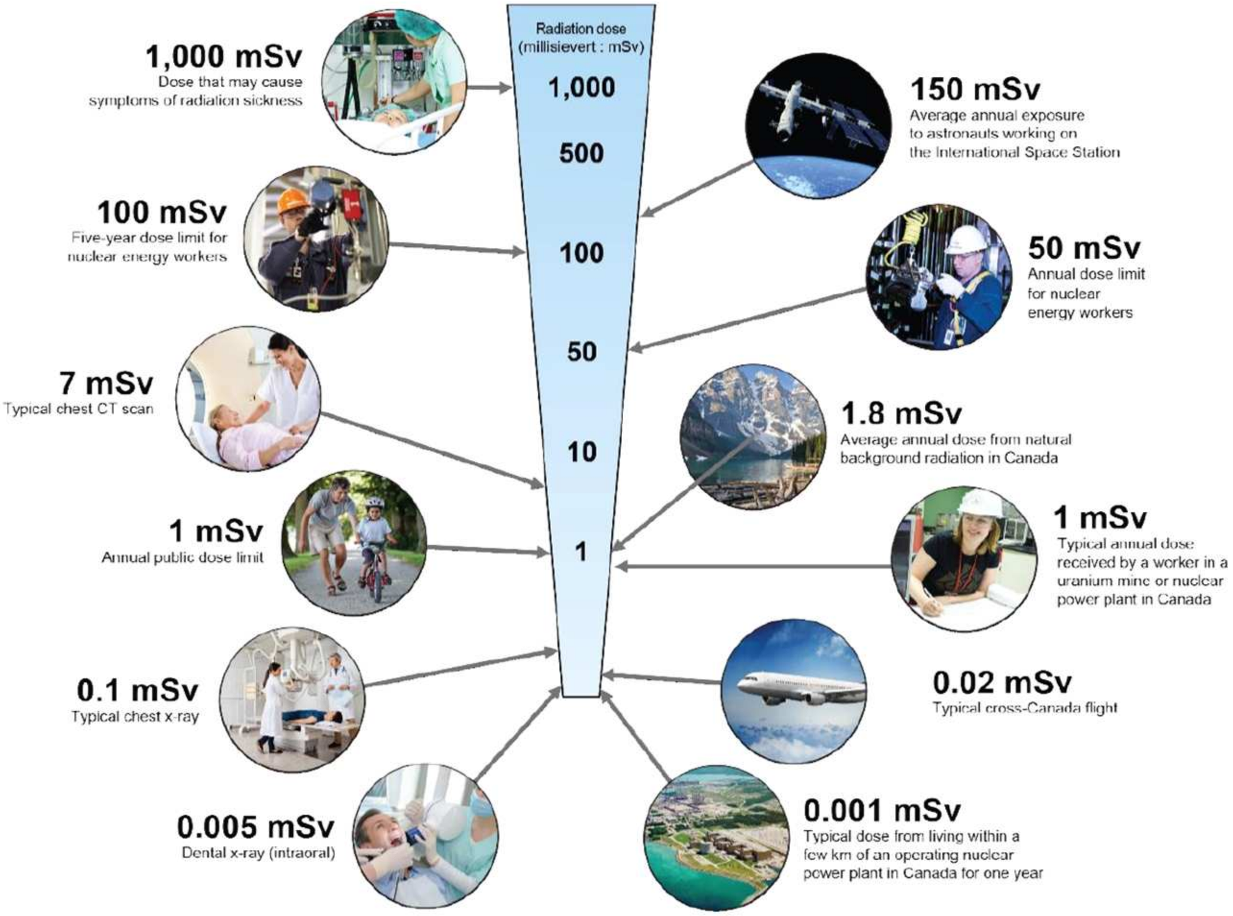


Figure 2-5 Typical Doses from Various Sources (CNSC 2020a)

In CNSC (2020a), the figure above is explained as follows: The typical annual dose from living within a few kilometers of a nuclear power plant is 0.001 mSv. An intraoral dental x-ray is 0.005 mSv. The dose from a typical cross-Canada flight is 0.02 mSv. The dose from a typical chest x-ray is 0.1 mSv. The CNSC sets the annual public dose limit at 1 mSv. A typical annual dose received by a worker in a uranium mine or nuclear power plant in Canada is around 1 mSv. The average annual dose from natural background radiation in Canada is 1.8 mSv. The dose from a typical chest CT scan is 7 mSv. The annual dose limit for nuclear energy workers is 50 mSv. The five-year dose limit for nuclear energy workers is 100 mSv. The average annual exposure to astronauts working on the International Space Station is 150 mSv. A dose that may cause symptoms of radiation sickness is around 1000 mSv (CNSC 2020a).

2.5 International Agencies/Organizations

Radiation may pose a hazard to human health and the environment. Various international organizations have been founded to provide scientific recommendations and guidance related to radiation.

The International Commission on Radiological Protection (ICRP)

The International Commission on Radiological Protection (ICRP) is an independent, international, non-governmental organization, with the mission to provide recommendations and guidance on radiological protection concerning ionizing radiation.

The ICRP was established in 1928 to respond to concerns about the effects of ionizing radiation being observed in the medical community. It was later restructured to better take account of uses of radiation outside the medical area and was given its present name in 1950. Since 1977 the ICRP has published its recommendations in its own series of publications called the Annals of the ICRP. Publications cover a range of topics such as:

- modelling the behaviour of radionuclides within the body (e.g., ICRP Publication #145);
- calculating and tabulating dose coefficients (e.g., ICRP Publication #144);
- offering recommendations on radiological protection for specific industries or situations (e.g., ICRP Publication #132: Radiological Protection from Cosmic Radiation in Aviation);
- compiling nuclear decay data (e.g., ICRP Publication #107);
- compiling information on radionuclide behaviour and transfer in the environment (e.g., ICRP Publication #114).

Two particularly relevant publications are ICRP Publication #60, and the more recent equivalent ICRP Publication #103, which outline the ICRP's recommendations on dose limits. As per ICRP Publication #103, the ICRP continues to recommend that the public dose limit should be expressed as an effective dose of 1 mSv in a year (ICRP 2007). Section 3.2 provides additional information on how the Canadian Nuclear Safety Commission (CNSC) uses the ICRP's recommendations to set dose limits in Canada.

Readers are referred to the ICRP's website for further information.

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) was established by the United Nations' General Assembly in 1955 and has undertaken broad assessments of the sources of ionizing radiation and its effects on human health and the environment (UNSCEAR 2020).

In pursuit of its mandate, UNSCEAR's Scientific Committee reviews and evaluates global and regional exposures to radiation (UNSCEAR 2020). The Committee also evaluates evidence of radiation-induced health effects in exposed groups and advances in the understanding of the biological mechanisms by which radiation-induced effects on human health or on non-human biota can occur (UNSCEAR 2020). These assessments provide the scientific foundation used by agencies of the United Nations to formulate international standards for the protection of the public, workers, and patients against ionizing radiation (UNSCEAR 2020).

Information collected by UNSCEAR on radiation quantities, exposures, and health-related effects, is used by many agencies around the world, including the ICRP and the CNSC (see Section 3.2).

Readers are referred to the UNSCEAR website for further information.

World Health Organization (WHO)

The World Health Organization (WHO) has also established a radiation protection program to protect patients, workers, and the public. Focusing on public health aspects of radiation protection, this program covers activities related to radiation risk assessment, management, and communication. The WHO also publishes information on radiological topics, such as:

- indoor air quality guidelines for radon;
- water quality guidelines which include radiological parameters;
- guidance on the development of medical uses of ionizing radiation; and,
- international health regulations, which include core national capacities that countries should meet regarding radiological/nuclear emergency preparedness and response.

Readers are referred to the WHO website for further information.

Following International Guidance

The NWMO follows international guidance in addition to Canadian regulations and guidance. For example:

- Dose coefficients from the ICRP are integrated into dose calculations directly, or through the use of Canadian standards such as CSA N288.1 (CSA 2014), which make use of ICRP values.
- Drinking water guidance levels from the WHO (WHO 2017), among other sources, are used to give context to baseline concentrations of radionuclides in water.
- Information from UNSCEAR (e.g., UNSCEAR 2010) is used to give context to radiation baseline levels in Canada and in comparison, to other parts of the world.

3 Regulation of Radiation in Canada

3.1 Overview of Agencies

In Canada, radiation and related facilities are regulated at the federal level. The main agencies involved in *regulation* include:

1. The Canadian Nuclear Safety Commission (CNSC); and,
2. Health Canada.

In addition, the Impact Assessment Agency of Canada (IAAC), which is accountable to the Minister of Environment and Climate Change is responsible for the assessment of the impacts of potential projects and thus contributes to informed decision making on major projects such as the proposed Project of implementing Canada’s plan for the long-term management of used nuclear fuel by NWMO.

Information on each of these is provided in the following subsections.

3.2 Canadian Nuclear Safety Commission (CNSC)

The Canadian Nuclear Safety Commission (CNSC)

In Canada, the use of nuclear energy and materials and related facilities (such as the proposed DGR) are regulated at the federal level to ensure the safety of all Canadians from radiation. The CNSC is the primary federal regulator.

Under the *Nuclear Safety and Control Act* (*NSCA*), the CNSC’s mandate involves four major areas (CNSC 2014a):

- regulation of the development, production and use of nuclear energy in Canada to protect health, safety and the environment;
- regulation of the production, possession, use and transport of nuclear substances, and the production, possession and use of prescribed equipment and prescribed information;
- implementation of measures respecting international control of the development, production, transport and use of nuclear energy and substances, including measures respecting the non-proliferation of nuclear weapons and nuclear explosive devices;
- dissemination of scientific, technical and regulatory information concerning the activities of CNSC, and the effects on the environment, on the health and safety of persons, of the development, production, possession, transport and use of nuclear substances.

Those wishing to carry out activities related to the site preparation, construction, operation, decommissioning and closure of nuclear facilities in Canada must first obtain a licence from the CNSC.

Multi-Stage Regulatory Process

The CNSC's regulatory framework involves the *Nuclear Safety and Control Act* (*NSCA*) and other laws passed by Parliament which govern the regulation of Canada's nuclear industry, as well as regulations, licences, and documents that the CNSC uses to regulate the industry (see Figure 3-1) (CNSC 2021b). The regulatory framework also includes guidance, which is used to inform the applicant or licensees on how to meet requirements, elaborate further on requirements, or provide best practices. CNSC requirements and guidance take into account international regulatory best practices and modern codes and standards, and align with the International Atomic Energy Agency's Safety Fundamentals and Safety Requirements.

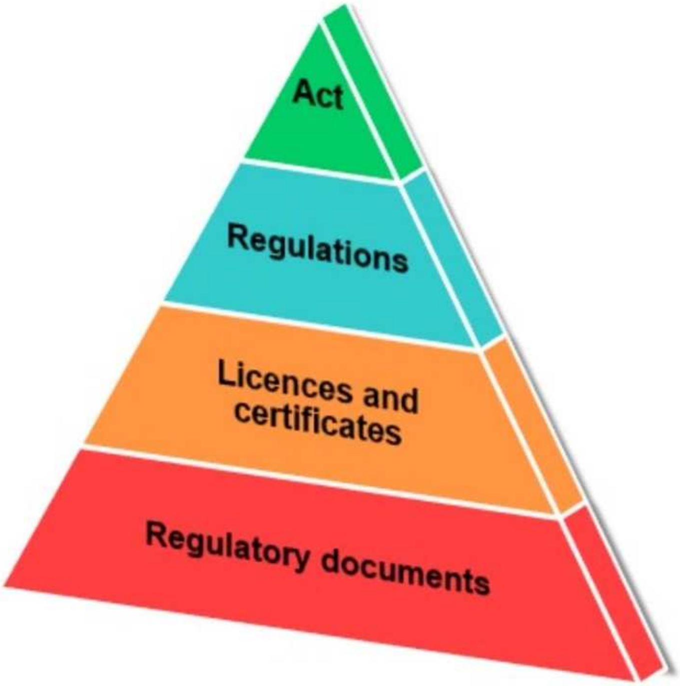


Figure 3-1 Key Elements of the CNSC's Regulatory Framework (CNSC 2021b)

The CNSC generally regulates by issuing licences under which specific activities (those outlined in the licence) can be undertaken, by a licensee. Therefore, entities (such as a business) cannot simply undertake projects; instead, they must *first* navigate the CNSC's licensing process and obtain a licence. Furthermore, *before* starting a phase of a facility's lifecycle, a licence covering the activities that will be undertaken in that phase must be obtained and each one of these licences or amendments requires careful assessment and approval. Overall, this means that projects are regulated carefully, and in a step-by-step process. Licensing continues throughout operations, and licencing continues after operations have ceased. This ensures that there is CNSC oversight of nuclear projects in Canada.

CNSC Dose Limits

Under the NSCA, the Canadian *Radiation Protection Regulations* set limits on the amount of radiation the public and nuclear energy workers may receive. In Canada, the effective dose limits for the public is 1 mSv in one calendar year. The effective dose limits for a nuclear energy worker is set at 50 mSv in any one year and 100 mSv in five consecutive years. The dose limit for pregnant workers is 4 mSv from the time the pregnancy is declared to the end of the term. In addition, licensees must ensure that all doses are as low as reasonably achievable, social and economic factors being taken into account. Regular reporting and monitoring demonstrate the average annual doses to the most exposed workers (e.g., industrial radiographer) are approximately 5 mSv per year (CNSC 2020d) and the average dose for all nuclear energy workers is 1 mSv per year (see Figure 2-5).

According to CNSC (2021c), the post-closure safety assessment of a disposal facility also needs to account for the possibility of exposure to multiple sources, and their potential cumulative effects, and to help ensure that doses resulting from the disposal system are as low as reasonably achievable, a dose constraint, or administrative level, should be established by the operator as a fraction of the regulatory annual dose limit. The dose constraint is not a limit, but rather a design tool in the optimization process. For example, for optimization, the ICRP recommends a dose constraint of 0.3 mSv/year. This dose constraint is used in the present post-closure assessment discussed in this study.

Dose Limits - What is Safe?

As discussed in CNSC 2019b, the word “safe” means different things to different people. For many, the idea of being safe is the absence of risk or harm. However, the reality is that there is a level of risk in almost everything we do. For example, speed limits on roads are set to optimize safety. Nevertheless, accidents occur even when drivers are obeying the speed limit. Despite the risks, we make a conscious decision to drive. Similar conscious decisions are made when radiation is used. Radiation exposure carries a potential health risk. Knowing what the risks are helps the CNSC and other regulatory bodies set dose limits and regulations that limit exposure to an acceptable or tolerable risk (some may even say a safe limit).

The CNSC and other international regulators also put measures in place, including stringent dose limits and radioactive source tracking databases, to mitigate the chances of the public or workers receiving doses of radiation high enough to cause undue effects (CNSC 2019b). The CNSC also has strict regulations on how nuclear substances and devices must be handled in Canada (CNSC 2019b).

To set dose limits, the CNSC has largely adopted the recommendations of the ICRP. The ICRP looked at the assessment of radiation effects by scientific bodies such as the UNSCEAR and BEIR (U.S. National Academy of Sciences, Biological Effects of Ionizing Radiation). The ICRP then determined what they call the overall “detriment” of radiation exposure , which includes (CNSC 2019b):

- the probability of inducing a fatal cancer;
- the chance of a non-fatal cancer occurring;
- the chance of severe hereditary effects; and,
- the length of life loss if the harm occurs.

Using all these risks, the ICRP has calculated an overall detriment of 0.042 (4.2%) per sievert for adult workers and 0.057 (5.7%) per sievert for the whole population. (CNSC 2019b). This means, for example, that a person would have a 5.7% chance of a significant health effect after receiving a radiation dose of 1 Sievert (recalling that 1 sievert is equal to 1000 milli-sieverts).

A 1 sievert dose would therefore be a high dose. Regulatory agencies such as the CNSC therefore set dose limits much less than this, in order to ensure that there is very low risk to workers and even less to public. In Canada, the annual dose limit for members of the public is set to 1 millisievert - one thousandth of a sievert.

In determining this limit, the agencies assume that there is no threshold, and that every exposure to radiation carries some risk. In particular, the Linear No-Threshold model (LNT) risk model is used internationally. The LNT conservatively assumes there is a direct relationship between radiation exposure and cancer rates (CNSC 2019b). A dose of 1 millisievert would imply a risk to an average person of less than one in a million based on the above ICRP risk factor. A dose of 1 millisievert is also smaller than the dose that an average Canadian already receives from natural sources of about 1.8 millisievert (Grasty and Lamarre 2004).

Furthermore, there is a Canadian regulatory requirement to not simply meet the dose limit, but to reduce all doses as low as reasonably achievable (ALARA), social and economic factors being taken into account (CNSC 2019b). This is commonly referred to as the ALARA principle.

As a result of these regulations, the Canadian public rarely, if ever, approaches the annual dose limit due to nuclear power activities. Doses to the public are generally well below one-tenth of the CNSC's dose limit, or about 0.1 millisieverts, even for those living near nuclear facilities, and much smaller for those living further distant (CNSC 2019b). (See Section 8.1)

3.3 Health Canada

Health Canada also plays a key role in protecting Canadians from the risks associated with radiation exposure. It is the lead federal department responsible for the Federal Nuclear Emergency Plan, and it is one of the key departments supporting the Comprehensive Nuclear Test Ban Treaty (NRCan, 2017). It also administers the National Radon Program, the National Dose Registry, and the National Dosimetry Services program (HC 2020).

As outlined in HC (2020), Health Canada's Radiation Protection Bureau is responsible for delivering Health Canada's environmental and occupational radiation protection program. The program informs Canadians, other government departments and agencies, and stakeholders (provinces/territories, health professionals and associations, industry, etc.) about the health risks linked with ionizing radiation, and ways to manage these risks. The Bureau is composed of four divisions: the Radiation Surveillance Division; the Radiation Health Assessment Division; the Nuclear Emergency Preparedness and Response Division; and the National Dosimetry Services. Key activities of the program are monitoring environmental and occupational radiation, working with international partners, managing federal nuclear emergency preparedness and response (such as training and maintaining plans and procedures for a coordinated federal response), and conducting radiation-related research. In addition, the Bureau educates Canadians and stakeholders on the health risks of radon and provides advice on ways Canadians can reduce their potential exposure. The Radiation Protection Bureau's website can be accessed using this link: https://www.canada.ca/en/health-canada/corporate/about-health-canada/branches-agencies/healthy-environments-consumer-safety-branch/environmental-radiation-health-sciences-directorate/radiation-protection-bureau.html.

3.4 Impact Assessment Agency of Canada

The Impact Assessment Agency of Canada (IAAC) administers Canada's Impact Assessment process based on the new *Impact Assessment Act* enacted in 2019. The IAAC, through its delivery of impact assessments, serves Canadians by looking at both positive and negative environmental, economic, social, and health impacts of potential projects (IAAC 2020).

The *Impact Assessment Act* applies to the proposed implementation of Canada's plan for the long-term management of used nuclear fuel by NWMO and therefore, an Impact Assessment must be completed for this Project in addition to the CNSC licensing.

4 Overview of the Project

4.1 Main Project Phases

The complete lifecycle of the Project of implementing Canada’s plan for the long-term management of used nuclear fuel by NWMO, can be broken down into the following six (6) major phases following a site selection process:

1. Site Preparation;
2. Construction;
3. Operations;
4. Extended Monitoring;
5. Decommissioning and Closure;
6. Post-closure Monitoring.

The facility will not be immediately abandoned after closure. In accordance with CSA N292.7, institutional control arrangements for the post-closure phase would be in place, prior to the commencement of facility closure.

A brief description of each of these phases is provided in the subsections below, based on information in NWMO (2016a) and NWMO (2021d).

Site Selection Process

The NWMO began the site selection process in 2010. The process is designed to ensure safety, security and protection of people and the environment. Several technical assessments were conducted, along with community engagement, to narrow the list of potential sites and focus on those with the strongest potential to meet the Project’s criteria and where communities continue to be interested in exploring the Project (NWMO 2016a).

Once the site selection assessments are finished, a preferred site, with informed and willing host communities, will be selected and undergo more detailed characterization (NWMO 2016a). Site selection is expected to be completed in 2024.

Site Preparation Phase

The site preparation phase includes activities such as clearing existing vegetation from planned building footprints, grading the site, fencing off the site, and installing initial utilities and infrastructure. Initial utilities and infrastructure include things like electricity, stormwater management systems, clean water and sewage systems, and fuel tanks, though some of these may be temporary setups at this phase (NWMO 2016a).

It is important to understand that the site preparation phase does not involve the presence of used nuclear fuel on site.

Construction Phase

Construction phase includes building the surface facilities as well as the underground repository. For planning purposes, the NWMO has assumed the construction phase could require about 10 years (NWMO 2016a).

It is important to understand that the construction phase does not involve the presence of used nuclear fuel on site.

Operations Phase

The operations phase includes the main process of receiving shipments of used nuclear fuel (in Used Fuel Transportation Packages, see example in Figure 4-1), repackaging into Used Fuel Containers, transferring them into the underground facility and emplacing them in the underground repository.

The above-ground activities would take place within the Used Fuel Packaging Plant. This is where used nuclear fuel would be transferred from the Used Fuel Transportation Packages to their Used Fuel Containers, sealed, inspected and dispatched for placement in the underground repository (the Deep Geologic Repository, or ‘DGR’) (example in Figure 4-1). Most steps in the packaging process would be remotely operated, taking place in radiation-shielded rooms. Ventilation air would be filtered and monitored before it would leave the facility (discussed in greater detail in later sections) (NWMO 2016a).

In the underground facility (the DGR), placement rooms (i.e., the rooms where the Used Fuel Containers are placed for disposal) would be backfilled and sealed as they become filled. The tunnels, however, would remain open to allow for monitoring until decommissioning and closure (see the next phase).

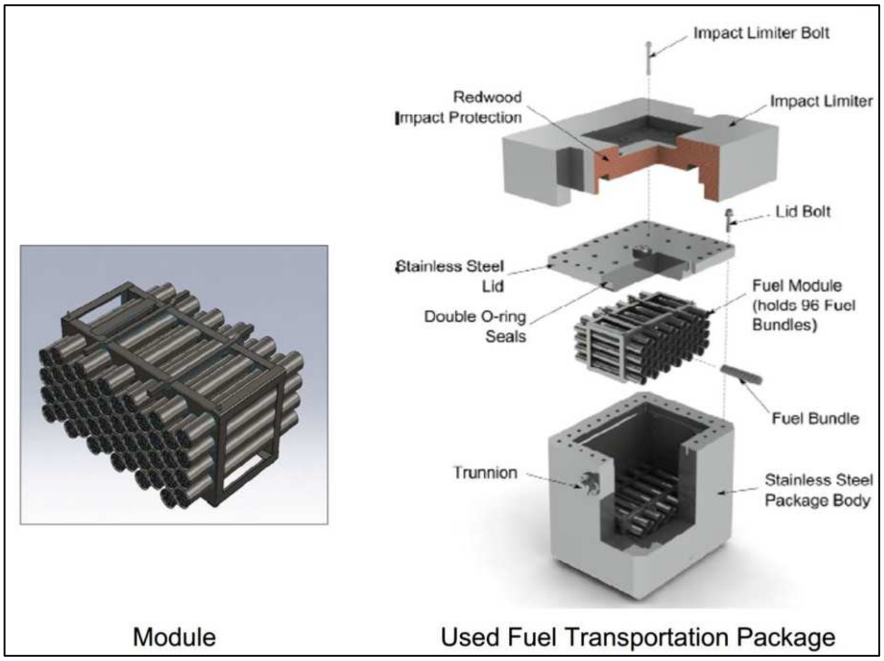


Figure 4-1 Module and Used Fuel Transportation Package (NWMO 2021d)

<u>Extended Monitoring Phase</u>

Once all Used Fuel Containers have been emplaced in the repository, the NWMO would continue to monitor the long-term safety and performance of the repository for an extended period of time. During this phase, the placement rooms would remain backfilled and sealed, but access tunnels and perimeter tunnels and shafts would be open and maintained in order to support the underground monitoring activities (NWMO 2016a).

The extended monitoring phase could last several decades; 70 years has been assumed for planning purposes (NWMO 2021d). The actual duration of this phase would be informed by discussion with the regulator and with input from the communities (NWMO 2016a).

<u>Decommissioning and Closure Phase</u>

Decommissioning activities would begin after enough monitoring data have been collected to support the decision to decommission and close the repository. The main activities during the decommissioning and closure phase would include (NWMO 2021d):

- sealing the underground access tunnels, perimeter tunnels, service areas and the shafts;
- decontamination and decommissioning of surface facilities and infrastructure;
- sealing of all subsurface boreholes and any surface boreholes not required for post-closure monitoring; and,
- closure of any other remaining facilities.

Once complete, the repository would be closed and sealed, at which point the site would be graded and landscaped based on the end-state land use agreed to with the communities (NWMO 2016a).

It is anticipated that permanent markers would be installed to inform future generations of the presence of the sealed repository (NWMO 2016a). For planning purposes, the NWMO has assumed the decommissioning and closure phase would require about 25 years (NWMO 2021d).

Post-closure (Long Term)

The repository is designed to be passively safe after closure, with no need for human intervention and maintenance (NWMO 2016a). The careful site selection work early in the Project will also help ensure that the facility would perform as planned for a long period of time.

Post-closure monitoring would be in place for as long as needed in order to verify that the repository is operating safely (NWMO 2016a).

Again, the key point is that a repository would be sited and designed so that the potential long-term impacts would be very low even to a future person assumed to be living unknowingly, directly above the repository, and drawing water from a local well. The nature of the rock layers surrounding the repository would limit movement of radionuclides through the surrounding rock and into any permeable groundwater systems (NWMO 2016a).

It is important to note that the Used Fuel Containers are retrievable, though this becomes progressively more challenging as the repository is sealed during the decommissioning and closure phase. For example, the difficulty increases with each step as the buffer backfill is added, the concrete bulkhead is installed, the room seal is added, the access tunnel is sealed, the perimeter tunnels are sealed, and the service areas and main shaft are sealed. Further information on retrievability is provided in NWMO (2021d).

4.2 Site Layout

As mentioned earlier, the site's surface facilities would provide the processes and equipment needed for receiving, inspecting, repackaging and moving used nuclear fuel to the main shaft for transfer underground and placement in the repository. The surface facilities would include the Used Fuel Packaging Plant, the shaft complexes, and the sealing material compaction plant, as well as support facilities such as the administrative buildings, security, water management facilities and power and water supply. The exact site layout has not yet been developed. However, an illustrative conceptual layout of these surface facilities is presented in Figure 4-2 below for discussion purposes.

Figure 4-2 Conceptual Illustration of Surface Facilities (NWMO 2021d)

There are two main components to the underground operations of the DGR: the Underground Services Area, and the main repository with its placement rooms. The Underground Services Area would provide a range of services to support the DGR, for example, offices, washrooms, maintenance shop, battery charging station (for battery-powered equipment), as well as services and equipment for rock excavation. An illustrative layout of the underground facilities is presented in a previous section, in Figure 1-1.

5 Operations Phase

5.1 Main Activities

As mentioned in Section 4.1, the main tasks that occur during the operations phase of the Project would involve:

- receiving incoming shipments of used nuclear fuel contained within Used Fuel Transportation Packages;
- repackaging the used nuclear fuel into Used Fuel Containers designed for disposal;
- sealing and inspecting the Used Fuel Containers;
- placing the Used Fuel Containers into bentonite clay buffer boxes for disposal within the deep geologic repository;
- transferring the buffer boxes into the deep geologic repository;
- emplacing and backfilling the buffer boxes into the repository's rooms; and,
- sealing off the rooms once they are full.

It is important to note that most steps in the packaging process would be remotely operated, taking place in radiation-shielded rooms (NWMO 2016a).

5.2 Potential Releases and Mitigations

During operations, used fuel is received at the site, and transferred from the shipping packages to the underground packages, which are then placed underground. 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 radioactivity is contained within the fuel bundles. Therefore, the potential sources of radioactivity or radiation within the facility are the direct gamma and neutron radiation from the fuel bundles, and small amounts of gas or particulates that may be released from fuel during handling.

Fuel handling accidents within the facility would be very unlikely. Partly as the fuel handling is a simple transfer process. Also, the fuel is generating a small amount of decay heat, but not enough to cause an overheating accident, so it does not require water cooling. The facility itself will be robust, in part due to the thick walls used for shielding purposes.

Potential releases would be contained within the Used Fuel Packaging Plant through the following mitigation measures:

- Thick concrete and/or metal walls in the fuel handling areas, that provide gamma and neutron shielding.
- Fuel handling systems designed to minimize stress on fuel bundles, and to have them placed within sealed Used Fuel Containers as quickly as possible, to minimize releases.
- Air ventilation system, where air is directed inwards to the higher radioactivity areas, and then filtered and monitored before release through building stack.
- Dry decontamination and cleanup methods for clearing most surfaces.
- Process water treatment system, where any water used for washing or decontamination is cleaned, filtered and monitored before recycling or release.
- Monitoring equipment and shutdown capability.

5.3 Pre-closure Safety Assessment

The public may still be exposed to the very small levels of radionuclides and radiation remaining after shielding, treatment and filtration. Therefore, the NWMO will prepare an operational safety assessment (also referred to as a Pre-closure Safety Assessment, PreSA).

The PreSA will consider the design and safety features of the DGR, the potential releases, and the potential pathways by which people may be exposed to these releases. It will assess public exposures based on the estimated releases and compare them to regulatory criteria to ensure that there is no health risk to the public.

Preparation of the PreSA is an iterative process: As site and design details become further developed, the NWMO will update the PreSA; in turn, the design will be modified as needed to address priorities identified in the preliminary PreSA results.

The final version of the PreSA will support the Licence to Prepare Site application and will be independently reviewed by the CNSC as part of the licencing process. It will be prepared following the approach outlined in Canadian standards, guidelines, and applicable CNSC regulatory documents.

Preliminary work to inform the PreSA is underway, based on current site and design information. The final PreSA will not be ready until the Licence to Prepare Site application is submitted; however, summaries of preliminary PreSA results may be included in the annual Confidence in Safety reports.

The dose to members of public from normal operations is expected to be much less than the corresponding regulatory criterion (Kremer & Garisto, 2011).

Regarding decommissioning, dismantling of surface facilities, such as the UFPP, will be part of decommissioning activities. The facilities will be thoroughly monitored during their entire operational life to minimize contamination of the systems. A full characterization will occur prior to dismantling activities to assess any contamination which may be present. The best available technology, which may include robotics, will be selected to minimize worker dose to complete dismantling activities. Decommissioning of the surface facility will be subject to CNSC approval and oversight. As such, at this time, the NWMO is confident that doses during decommissioning will be bounded by those during operations.

Radon

Radon is a radioactive gas produced by the radioactive decay of uranium, thorium, and actinides. Although radon is produced from the decay of the used fuel, as noted in Section 2.3, radon is also naturally produced from the uranium and thorium present in the host rock of any repository site.

An initial assessment of the hazard posed by radon during the construction and operation of the DGR was completed by NWMO (NWMO 2020). This assessment provided the following dose estimates:

- for members of the public close to the facility (i.e., 100 m from the release point), the dose rate contribution from radon emitted from the facility, during the construction phase, is 0.00011 mSv/y.
- for members of the public farther from the facility (i.e., 1,000 m from the release point), the dose rate contribution from radon emitted from the facility, during the construction phase, is 0.000019 mSv/y.
- for members of the public close to the ERMA (i.e., 100 m from the release point), the dose rate contribution from radon emitted from the ERMA is 0.0037 mSv/y.
- for members of the public farther from the ERMA (i.e., 1,000 m from the release point), the dose rate contribution from radon emitted from the ERMA is 0.00064 mSv/y.

All of these dose rate estimates are much less than the dose rate contribution from natural background sources. Additional details are provided in the NWMO report *Preliminary Radon Assessment for a Used Fuel Deep Geological Repository* (NWMO 2020). This analysis would be repeated specifically for the South Bruce site if that site is selected.

5.4 Conclusions on Confidence in Safety for the Operations Phase

Safety during the operations phase will be assessed as part of NWMO's Pre-closure safety assessment. The dose to members of public from normal operations is expected to be much less than the corresponding regulatory criterion. It is further expected that the potential radiological effects of the Project during closure and decommissioning, if any, will be less than - and therefore bounded by - the potential effects during operations. A preliminary safety assessment is underway based on current site and design information, with some results anticipated to be complete by the end of 2023. As the design progresses, and a site is selected, the assessment will be refined to reflect ongoing design improvements and site-specific features.

Section 7.1 provides examples and further details on ways in which NWMO would ensure safety during the operations phase.

6 Post-closure Phase (Long Term)

Information on the post-closure phase and its safety assessment are discussed in this section, based primarily on information from NWMO (2018a,b) and NWMO (2022).

6.1 Safety During the Post-closure Phase

The post-closure period would start at the end of decommissioning, after the shafts have been sealed and the surface facilities have been dismantled. In the post-closure phase, the site is assumed to remain under institutional controls for a period of time. Institutional controls can be defined as “control of residual risks at a site after it has been decommissioned” (CNSC 2021a). 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.

It is interesting to note that while the used fuel is safely stored at reactor sites at present, the current waste storage facilities only provide an interim solution in that they are not designed to safely store the used fuel for the duration of the hazard associated with it. In this sense, a DGR for used fuel would provide a safer solution than interim waste storage facilities, for the long term.

6.2 Evolution of the Repository System Following Closure

The post-closure phase is discussed in four timeframes.

Up to 1,000 years:

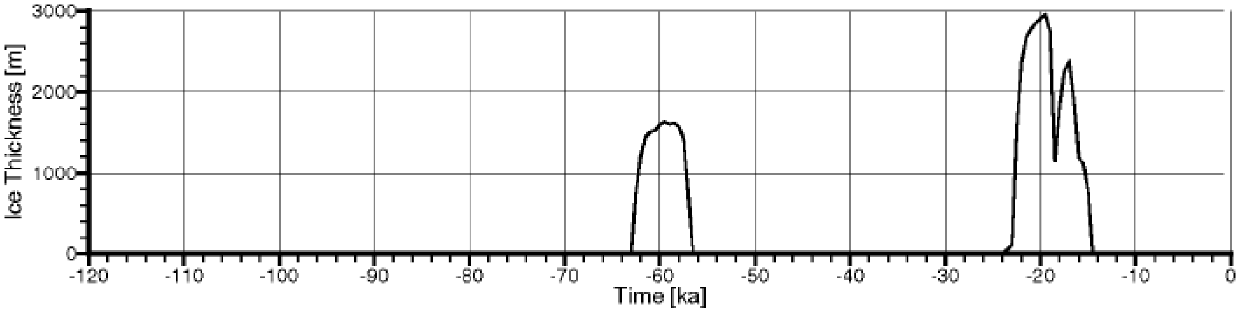
At the beginning of this time the facility would be decommissioned. As expected, deep groundwater would start to seep into the repository from the surrounding deep rock. This will allow the bentonite materials to hydrate, swell, and seal the repository. Especially during the first 500 years, radioactivity and heat in the used nuclear fuel would decrease significantly due to the decay of most of the fission products. The containers would reach a peak temperature of up about 92°C and then start cooling down. This is less than the targeted maximum temperature of 100°C. Temperature is accounted for in the repository layout.

1,000 – 60,000 years:

This represents conditions with no glaciation coverage of the site. The surrounding sedimentary rock would reach its peak temperature and largely cool back down to natural ambient temperatures. Surface conditions would likely change reflecting human activities and natural evolution of the environment, possibly in response to processes such as climate change. Although the overall climate would likely remain temperate, climate change could include global warming in the near term *and* the advent of cooler climate in the long term.

60,000 – 1,000,000 years:

Over this period the main perturbations in the system would no longer be driven by the repository. Instead, there would be natural regional-scale changes that in turn may be transmitted to the repository. In particular, climate change initiated by long-term changes in solar insolation patterns may occur, leading to initiation of a new glaciation cycle. Figure 6-1 illustrates possible ice-sheet thicknesses over the site in the future, based on reconstruction of the past ice sheet coverage during the last glaciation period, showing ice sheet thickness over the site reaching peaks at 60,000 years in the future and 100,000 years in the future. Based on past history, several cycles of glaciation are likely to occur over the next million years.



NOTE: This is a reconstruction of ice sheet thickness over the repository site (during the last glaciation period) looking backwards in time. For the post-closure phase, the present-day starts at -120ka on this this figure and advances.

Figure 6-1 nn9930 Glacial System Model Outputs for the Grid Block Containing the Repository Footprint for this Study (NWMO 2018a)

1,000,000 years and beyond:

At these times, the repository would become a relatively passive feature of the geosphere, in quasi-equilibrium with the surrounding rock. The dominant processes would be natural regional perturbations to the geosphere that in turn affect the repository. Over this period, changes would mainly be due to the result of slow-acting tectonic forces, e.g., movement of Earth’s tectonic plates, and cumulative erosion or deposition processes.

Beyond one million years, radioactivity in the used nuclear fuel bundles would become similar to that in an equivalent amount of natural uranium found in a uranium ore body and similarly buried deep underground. And in the South Bruce area, where the proposed repository rock formation is over 300 million years old, the geoscientific evidence supports the long-term stability of this sedimentary rock environment and its resilience to change on timescales beyond one million years (see Section 7.2).

6.3 Post-closure Safety

The DGR is designed to contain and isolate the radioactivity in the used fuel for very long times. For example, the copper-coated containers should last longer than one million years under the expected geological conditions outlined in Section 6.2. In this scenario, the public exposure is zero.

However, it is possible that some containers will fail, and that there will be some release of radioactivity over these long timeframes. In this scenario, however, the durability of the fuel bundle materials, the clay barriers and the geosphere will still act to retain radionuclides deep underground, and allow them time to decay to non-radioactive materials. In this case, the public may be exposed to the very small levels of remaining radionuclides. A post-closure safety assessment is therefore prepared by the NWMO that considers the design and safety features of the DGR, the potential releases, and the potential pathways by which people may be exposed to these releases. This Post-closure Safety Assessment (PostSA) will be prepared by NWMO, reflecting these design developments. The PostSA will assess public exposures based on the estimated emissions and compare them to regulatory criteria to ensure that there is no health risk to the public.

The PostSA will follow the approach outlined in Canadian standards, guidelines, and applicable CNSC regulatory documents. A preliminary safety assessment is anticipated to be complete by the end of 2023, based on current site and design information. The NWMO will update the assessment as the site and design details improve. And the design in turn will be modified as needed to address priorities identified in the preliminary safety assessment. Ultimately, this assessment will be independently reviewed by the CNSC as part of the licencing process. It is expected that the potential radiological effects of the Project during post-closure, if any, will be less than the potential effects during operations.

6.4 Results of an Illustrative Post-closure Safety Assessment

Several major PostSAs for a deep geological repository for used CANDU fuel, located at hypothetical sites in either crystalline rock or sedimentary rock, have been carried out over the past 10 years or so (NWMO 2012, 2013, 2017, 2018). Similar studies have also been published in other countries, notably Sweden (SKB 2011a; SKB 2011b), France (IAEA 2016; Andra 2016; Andra 2005), Finland (Posiva 2007; Posiva 2012; Posiva 2021), Japan (JNC 2000, NUMO 2021) and Switzerland (Nagra 2002). Although the geologic environment and details of the repository concept varied from study to study, all studies found that disposal of used nuclear fuel in a deep geological repository was a safe and viable option for protecting humans and the environment from the long-term hazards of used nuclear fuel.

A brief summary of the results of the most recent Canadian PostSA for a sedimentary rock setting (such as for the South Bruce site) is provided to illustrate the effectiveness of the deep geological concept in the sedimentary rock setting (NWMO 2018a). This assessment was not conducted specifically for the South Bruce site, so is only illustrative of the potential conclusions for this site. Site-specific assessments are presently underway.

Understanding Scientific Notation:

PostSAs often involve numbers that are very small or very large. Scientific notation is used because it makes very large and very small numbers easier to write compared to the decimal system. Using scientific notation, numbers are written, for example, as: 2.9x10^{-11}. Here, "2.9" is called the coefficient, "x10" is called the base, and "-11" is called the exponent. Written in decimal form this number would be 2.9 with the decimal moved 11 times to the left (left is indicated by the negative symbol, whereas a positive symbol would mean to the right). So, 2.9x10^{-11} is 0.000000000029, whereas 2.9x10^{+11} is 290,000,000,000. Sometimes the base (i.e., "x10") is replaced with "E", and written as 2.9E-11, which is the same.

6.4.1 Receptors

The PostSA adopts scientifically informed, physically realistic assumptions for processes and data that are understood and can be justified on the basis of the results of research and/or future site investigations. Where there are high levels of uncertainty associated with processes and data, conservative assumptions are adopted and documented to allow the impacts of uncertainties to be bounded.

For example, to ensure that dose rates are not underestimated, conservative assumptions are made concerning the characteristics of the potential human receptors. Specifically, it is assumed that some potential receptors are self-sufficient and spend all their lives in the vicinity of the repository, unknowingly living on top of the repository and obtaining all of their drinking water and crop irrigation water from a deep well, with the well positioned in the location that maximizes the uptake of any potential radionuclides released from the repository. Their food includes plants grown in a garden, domesticated animals and fish. All plant and animal biota used as food are subject to potential contamination from surface water, soil and air. These receptor characteristics are consistent with more self-sufficient than typical current habits and lead to an overestimate of the impact. In this illustrative study, this imaginary receptor was labelled as the Self-Sufficient Farmer.

In addition to this imagined receptor with maximum potential exposure, the PostSA also considers other potential human receptors that could be living in the vicinity of the repository. These include more accurate representative characteristics of people living in the area now. In general, these more realistic receptors have much less exposure to the repository, often factors of 100 times less exposure.

6.4.2 Normal Evolution Scenarios

Given the long time frame of interest, the PostSA does not define a single future, but rather considers a range of future scenarios. The Normal Evolution Scenarios consider likely futures. The Normal Evolution Scenario is here assessed in terms of a Reference Case and a series of sensitivity studies. The Reference Case represents the expected situation in which all repository components meet their design specification and function as anticipated. As such, the Used Fuel Containers remain intact essentially indefinitely, and no contaminant releases occur in the one-million-year time period of interest. Radiological dose rates to the public and the environment are therefore zero.

Sensitivity studies illustrate repository performance for a range of reasonably foreseeable deviations from key Reference Case assumptions. These deviations arise as a result of components placed in the repository that either (a) do not meet their design specification or (b) do not fully function as anticipated.

The likelihood of such deviations will be low. Care is being taken to design, develop and test a robust fabrication and placement technology which would ultimately be implemented under a comprehensive quality assurance program. A key element of the quality assurance program would be an inspection process designed to ensure all placed components meet design specification. Similarly, component performance is supported by an extensive research and testing program, such that the behaviour of all materials placed in the repository will also be well understood.

Nevertheless, given the large number of containers, it is not unreasonable to anticipate that some container failures may occur. To illustrate repository performance in the presence of failed containers, the “Base Case” sensitivity study assumes a small number of containers are fabricated inadvertently with sizeable defects in their copper coating, and that a smaller number of these off-specification containers escape detection by the quality assurance program and are unknowingly placed in the repository.

In this study, 10 defective containers are considered sufficient to illustrate repository performance and to provide a measure of the consequences that could be expected should such an event (or a similar one) actually occur. The container defects are assumed sufficiently large to cause each of the 10 containers to fail within one million years (NWMO 2018a). As the actual nature (size, location) of each defect will vary, it is highly unlikely that 10 containers would all fail simultaneously; therefore, the failure times are assumed to be evenly spread over the one-million-year time period of interest, with the first failure occurring at 1000 years and subsequent failures occurring every 100,000 years.

For the Base Case, and for an assumed Self-Sufficient Farmer living on the repository site, the estimated maximum dose rate over one million years is very low (i.e., 6×10^{-10} mSv/y). This is so far below the average Canadian background dose rate of 1.8 mSv/y and the 1 mSv/y CNSC public annual dose limit that it can be considered zero. Dose rates are low because of the very slow rate at which water travels through the host rock and the absence of fractures.

I-129 is the only potential dose contributor. This is because I-129 has a sizeable initial inventory, a fraction of it is instantly released as soon as water contacts the fuel, a very long half-life, is not solubility limited, is non-sorbing in the buffer, backfill and geosphere and may have a radiological impact on humans who may be exposed to it. Other fission products and actinides either decay away or are released very slowly as the fuel dissolves and are thereafter sorbed in (essentially ‘stuck within’) the engineered barriers and geosphere. They mostly decay there before reaching the biosphere, or the accessible environment.

6.4.3 Sensitivity Cases

Many sensitivity cases were analyzed for the Normal Evolution Scenario to examine the effect of uncertainties on calculated impacts. The deep geological repository is a multiple-barrier concept (with both physical and chemical barriers). The sensitivity cases considered unexpected failures of physical barriers such as the fuel, container, seals (buffer and backfill) and geosphere, as well as chemical barriers such as the fuel and Zircaloy dissolution rates, radionuclide solubility, and radionuclide sorption (i.e., the influence of radionuclides adhering to solids instead of transporting in water).

The results of all these sensitivity studies indicate that the repository system is robust, and unexpected failures of one or several of these barriers would not impact the safety of the deep geological repository. The largest changes to the calculated dose rates are due to (1) changes in the number of failed containers from 10 to 1000, (2) changes to the values used to represent diffusion in bentonite and in the geosphere, and (3) assumptions around post-glaciation lifestyle. Even in these cases the calculated human dose rate in the first million years is many factors of ten less than the CNSC public dose limit of 1 mSv/y. And even at times greater than one million years after repository closure, the calculated peak dose rates remain well below the annual dose limit.

6.4.4 Disruptive Scenarios

The Disruptive Scenarios postulate the occurrence of unlikely events leading to possible penetration of barriers and abnormal loss of containment. Hypothetical Disruptive Scenarios examined in the NWMO (2018a) assessment included:

- “All Containers Fail” scenario;
- “Repository Seals Failure” scenario;
- A scenario with an “Undetected Fault close to the DGR”;
- Inadvertent Human Intrusion.

Other disruptive scenarios were also reviewed; but considered to be incredible, bounded by other scenarios, or inconsequential (see NWMO (2018a) for details).

All Containers Fail Scenario:

As would be expected, the highest calculated dose rates occur for the hypothetical “All Containers Fail” Scenario. In this study, it was assumed that all the containers failed due to unexpected conditions under an ice sheet at 60,000 years. However, even for this highly improbable scenario, the calculated dose rates within the first million years are much lower than 1 mSv/y.

Repository Seals Failure Scenario

The Repository Seals Failure Scenario has a small effect (increase of about 1.4 times) on the peak impact as compared to the Base Case and would remain well below the annual dose limit.

Undetected Fault Scenario

The peak impact for the Undetected Fault Scenario increases by about a factor of 20 compared to the Base Case, still well below the annual dose limit.

Inadvertent Human Intrusion:

A borehole is assumed to be accidentally drilled into the repository in the future. In this case, all the barriers are bypassed and some used nuclear fuel material brought directly to surface. The calculated dose rates to the drill crew in this scenario are high. However, the probability of this scenario is very low. The probability is low since the repository would be placed deep in the bedrock away from natural resources which, along with land use controls or markers, makes the probability of this occurring very low. In particular, the repository is sited in a deep location away from natural resources which, along with land use controls and markers, make this very unlikely. It is in fact the purpose of a deep geological repository to make intrusion into the fuel wastes very difficult compared with indefinite surface storage.

6.5 Conclusions on Confidence in Safety for the Post-closure Phase

Recent safety assessments for other sites indicate that the radiological dose limit can be met with substantial margins during the post-closure period. This result is consistent with previous assessments of a deep geological repository in Canada, as well as with safety assessment studies in other countries. Therefore, no detrimental health effects are anticipated for members of the public from the Project's radiological emissions post-closure.

The PostSA will be refined as the engineering design is improved. It will also be refined to reflect increased understanding of the geology at the site based on on-going site-characterization work.

The results presented in this report are largely based on NWMO's 2018 PostSA (NWMO 2018a,b) of used nuclear fuel disposal in sedimentary rock, and on NWMO's 2022 Confidence in Safety Report (NWMO 2022), reflecting the current understanding of the long term safety of the repository.

7 Ensuring Safety

The following discussions outline the many ways in which the Project would uphold radiological safety.

7.1 Operations Phase

Ensuring safety during the operations phase focuses largely on minimizing releases and exposures during normal operating conditions. This section discusses the following examples as ways in which the Project would ensure safety during the operations phase:

- Controlled Site Access;
- Engineering, Design and Process Controls;
- Emission Controls;
- Health & Safety Program;
- Radiation Protection Program;
- Regular Maintenance;
- Emergency Preparedness;
- Monitoring Systems and Monitoring Programs;
- Thorough Assessment; and
- Monitoring to Control Safety of Food Supplies.

7.1.1 Controlled Site Access

The site boundary, and within this, the facility fence line, would have access controls. This would prevent unintended or unauthorized access to the site, which would help to minimize exposures to members of the public. Members of the public would not have *ongoing* occupancy within the site boundary. Members of the public could only be present transiently, for example, if admitted for a tour or a similar purpose.

Physical protection systems would include a perimeter barrier with a section (5 m) of cleared and unobstructed land on both sides of the barrier. In addition, a system of protective elements would be in place to provide multiple layers of delay, detection and assessment that are controlled through a central command post or security monitoring room. An example of a physical barrier at the vehicle entry point is shown in Figure 7-1 below (NWMO 2016b).

Figure 7-1 Vehicle Entry Point (NWMO 2016b)

7.1.2 Engineering, Design and Process Controls/Safeguards

<u>*General*</u>

The Project's nuclear facilities, such as the Used Fuel Packaging Plant, would be designed using basic safety principles to ensure protection of human health and the environment. These include for example (IAEA 1999):

1. Management principles such as establishing a safety culture that governs the actions and interactions of all individuals and organizations engaged in activities related to the nuclear facility, as well as regulatory control and licensing by an independent regulator (the CNSC);
2. Addressing technical issues, such as siting, design, and emergency preparedness; and
3. A Defence-in-Depth concept implemented at the facility to compensate for potential human and mechanical failures. The concept would include several levels of protection, including multiple barriers, preventing the release of radioactive material to the environment as well as protection of the barriers by averting damage to the facility and to the barriers themselves. Further measures would be included to protect the public and environment from harm in case these barriers are not fully effective. The Defence-in-Depth concept provides an overall strategy for safety measures and features of nuclear facilities, ensuring that no single human or equipment failure would lead to harm to the public. Even combinations of failures that are only remotely possible would lead to little or no harm.

Dose Reduction Through Engineering & Design

Within the above-ground Used Fuel Packaging Plant, all handling operations that involve used nuclear fuel would be completed within heavily shielded enclosures (NWMO 2021d). This includes for example, concrete shielding walls, radiation-shielding windows, and Closed-Circuit Television (CCTV) cameras for remote viewing (NWMO 2016b). Figure 7-2 shows, as an example, a shielded transfer flask used to move the loaded Used Fuel Container within the different processing areas.

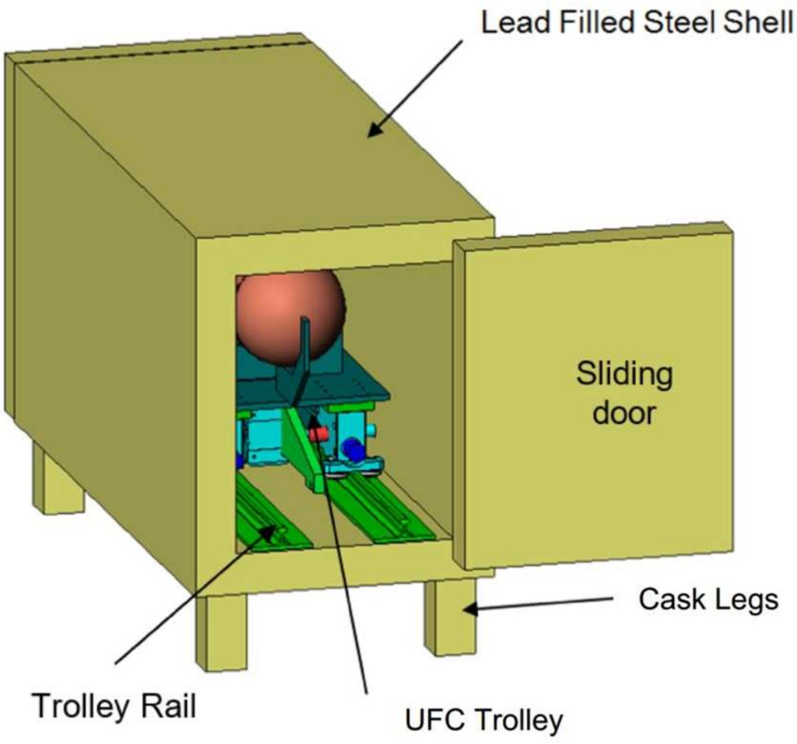


Figure 7-2 Shielded Transfer Flask Concept (NWMO 2021d)

As outlined in NWMO (2021d), areas with the highest activity and contamination hazards would generally be kept at the most negative pressure. Ventilation air would be filtered and monitored before it leaves the facility. As with any nuclear facility, very small amounts of radiation may be released as part of normal operations. But these releases are expected to be a very small fraction of regulatory limits.

It should be noted that all activities ***in the placement rooms*** would also be remotely controlled, once the first buffer box has been received at the room entrance (NWMO 2021d). An illustration is shown in Figure 7-3.

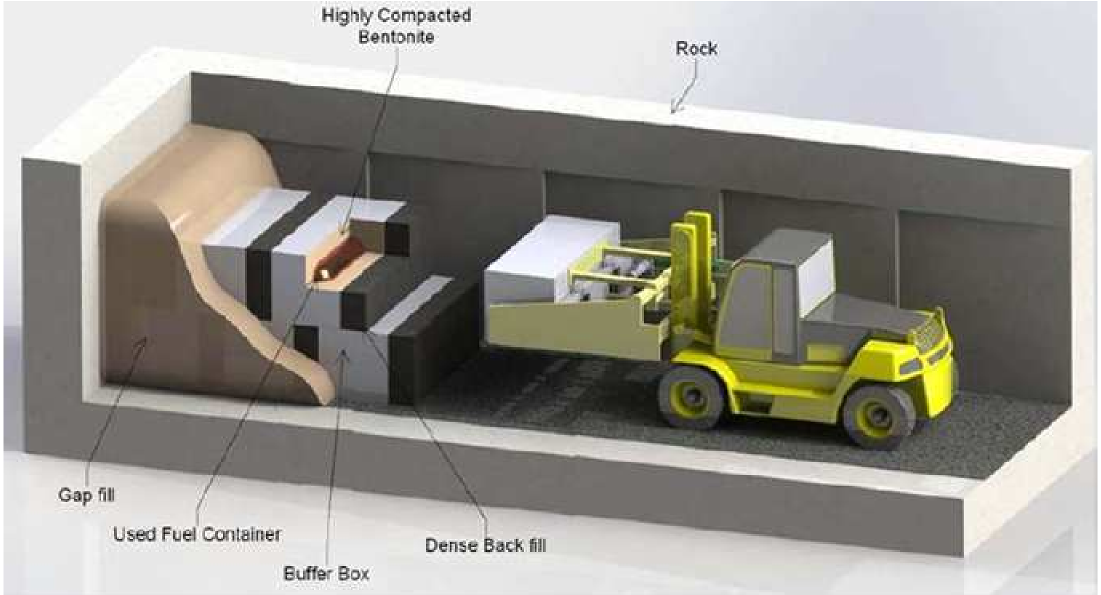


Figure 7-3 Schematic Illustration of Placement Room

7.1.3 Emissions Controls

On-site facilities would also use emission controls to reduce the quantity and/or undesirable characteristics of effluents. Examples of effluents and associated controls are discussed below.

Airborne Radioactive Effluent

Radiological air emissions would consist of radioactive particulates and gases from fuel handling.

These air emissions would be controlled by the use of filters.

Liquid Radioactive Waste

Liquid radioactive waste would be produced from decontamination of Used Fuel Transportation Packages and other equipment.

However, water usage in the Used Fuel Packaging Plant fuel handling areas would be minimized; for example, the fuel bundles would be stored and handled in air not water. Decontamination of Used Fuel Transportation Packages, after their fuel is unloaded, would be carried out using a combination of wet and dry decontamination methods. Decontamination of Used Fuel Transportation Packages would be mostly by dry decontamination, with the remaining contaminates removed using water, as required.

Liquid waste would be captured and sent to the radioactive liquid waste handling facility, where it would be processed, reused where possible, and only discharged when it meets discharge criteria. During normal operations, it is assumed that water would be processed through an appropriate treatment system and recycled or monitored before release.

Solid Radioactive Waste

Some radioactive solid waste would be produced during the operations phase. Modules and baskets from the incoming transportation packages would represent the most significant source of solid radioactive waste. When a module/basket has been emptied of its used nuclear fuel bundles, it would be processed including decontamination to achieve free-release limits, which would then allow shipment to offsite metals recycling facilities (NWMO 2021d). Other components would include used filters (from filtering exhaust air), spent ion-exchange media (from filtering liquid emissions), spent components (from maintenance of hot cell equipment), and low-level waste such as used cleaning materials and personal protective equipment (NWMO 2021d). All radioactive waste generated on site will be managed in accordance with applicable regulations and best practices.

7.1.4 Health & Safety Program

As discussed in NWMO (2021d), an occupational health and safety program would be in place and implemented for all phases in the evolution of the DGR when there would be workers actively involved. As the Project’s components involve underground construction and operation as well as the handling of used nuclear fuel, there would be extensive industrial and radiological components to the program.

7.1.5 Monitoring Systems

An environmental monitoring system would be established by the NWMO to monitor potential environmental effects, optimize facility performance and demonstrate regulatory compliance. NWMO’s environmental monitoring program would include, at a minimum, the following components (NWMO 2021d):

- Groundwater monitoring;
- Radiation monitoring;
- Stormwater/surface water monitoring;
- Air quality monitoring (above and below ground);
- Meteorological monitoring; and
- Seismicity and vibration monitoring.

Quality assurance / quality control procedures would be implemented throughout the monitoring programs to ensure thoroughness and accuracy of data. In this regard, the monitoring programs would include the following measures (among others) to ensure a high degree of confidence in the collected information:

- Strict adherence to standard protocols for the collection, preservation, storage, handling and shipping of samples and for sample collection;
- A field quality control program, including the submission of travel and field blanks and duplicate samples;
- Implementation of a quality control program for laboratory analyses; and
- Timely review of analytical results to identify areas of concern (including potential impacts).

Annual and quarterly status reports would be prepared to summarize the activities as related to the environmental monitoring program. The results of the ongoing Quality Assurance/Quality Control (QA/QC) activities would be incorporated in these reports.

7.1.6 Radiation Protection Program

Along with the radiation monitoring program, a radiation protection and control program would also be in place. In general, radiation protection programs are established at a facility to help ensure that no one receives a radiation exposure that exceeds the regulatory dose limit, and to ensure that radiation exposures are kept "As Low As Reasonably Achievable" (ALARA). Radiation protection programs typically focus on workers, but also have provisions that cover visitors, on-site, contractors, members of the public outside of the facility, etc. Radiation protection programs generally outline a variety of measures that are used to achieve their goals. These measures can be physical or design-based, such as having shielding materials built into the facility. They can be procedural, for example, outlining specific procedures that are to be followed when performing certain tasks, developed in such a way that following the procedure reduces exposure. They can also be administrative, such as limiting the amount of time that someone has to perform an activity, or limiting the number of times they can perform certain activities, again with the intention of reducing their exposure. Radiation protection programs may also identify certain types of protective clothing or equipment that must be used when performing certain tasks.

The Project's radiation protection program would incorporate the following features (NWMO 2021d), as well as others:

- Use of personal dosimeters for all staff or visitors within the Protected Areas;
- Use of a multi-zone system where staff would be monitored when they travel between defined radiation safety zones (typically from higher to lower zones);
- A whole-body counter for personnel to use annually or quarterly;
- Fixed area gamma monitors located throughout the facility to gauge local dose rates at places routinely occupied by operating personnel;
- Air radiation monitors located throughout the facility, including the exhausts for ventilation systems; and,
- Radiation vehicle monitors (portable and fixed) at entry or unloading areas.

While the radiation protection program would be mainly focused on minimizing doses to workers, it would also benefit members of the public by emphasizing contamination control. It would help prevent radionuclides from leaving the facility, for example, on workers' clothing or shoes. For context, as mentioned in Section 2.3, the average internal public dose from inhalation of natural radon is about 1 mSv/a (NWMO, 2020).

7.1.7 Regular Maintenance

To reduce the likelihood of malfunctions and failures, maintenance of equipment and facilities, including safety checks and inspections, would be routinely undertaken (for more information see NWMO 2021d).

7.1.8 Emergency Preparedness

Emergency Response

Procedures for emergency response planning, notification of releases, and incident reporting, would meet CNSC requirements and include the use of incident command systems to meet the needs of any kind or complexity of situation. For severe incident management (e.g., extreme or violent weather, etc.), various emergency related resources would be available. These would include (NWMO 2021d):

- Pre-planned response procedures (including shutdown protocols);
- Pre-established post-emergency procedures including those for resuming operations;
- Off-site and on-site communications and management protocols, including regulatory notifications and public interaction;
- The services of an Emergency Response Team (ERT); and
- Pre-trained staff that have undergone regular training on emergency response issues.

The primary personnel involved in handling any emergency would reside within an ERT. These resources would also be supported by on-site and first aid responders, the DGR's various superintendents and shift managers, and may be supported by off-site community emergency services. Communications staff would be available to coordinate and assist in the required incident communications activities (NWMO 2021d).

Fire Suppression

The following discussion focuses on the underground systems to be put in place as related to fire detection and fire safety. An optimum suppression concept that balances worker and nuclear safety would be established (NWMO 2021d).

The underground portion of the DGR facility would have the following fire protection features (NWMO 2021d):

- Suitable fixed fire suppression systems and portable fire extinguishing equipment in any fire hazard area;
- Fire extinguishing equipment in the mine entrance and at shaft stations; and
- Permanent and portable refuge stations with safety apparatus like breathing equipment, emergency air systems and communication devices.

In addition, fire detection systems incorporating heat, smoke and carbon monoxide detectors at key points in the facility would also be set up (NWMO 2021d). Audible and visual alarms would be activated on detection by any instruments required to do so. A stench gas system would also be used to notify underground workers in the event of an emergency (NWMO 2021d).

All underground vehicles would also be fitted with fire detection and suppression equipment. In total, fire suppression would be achieved through the use of a number of systems both for the equipment and the underground environment (NWMO 2021d).

Breathing air requirements as prescribed by regulatory guidelines and worker health and safety protocols (as applied to firefighting, non-nuclear air contamination, etc.) would be followed (NWMO 2021d).

Coordination and Collaboration with Communities:

Additional emergency response support services that may be provided by the community are described in a community study entitled "Emergency Services Study Report" (DPRA & IEC 2022). The NWMO and the community would collaborate on the resources required for emergency response (NWMO 2022).

7.1.9 Thorough Assessment

Before operations begin, the facilities and processes would have undergone a thorough assessment and likely several iterations of assessment. The PreSA will encompass all expected normal operations. For the purposes of the IA, the PreSA verifies the robustness of the repository design and demonstrates that there are no adverse health impacts.

7.1.10 Third Party Monitoring

In addition to NWMO's environmental monitoring efforts, it is expected that CNSC will conduct a separate independent environmental monitoring program as for other nuclear facilities. It is expected that the CNSC program would monitor radionuclide levels in relevant vegetation, crops and animal products, and fish.

7.2 After Closure (Long Term)

The following subsections discuss the key features and processes supporting the long-term safety of the deep geological repository concept. The information in these subsections is from NWMO (2009) unless otherwise noted.

7.2.1 Multiple-Barrier Concept

Reason 1: The DGR uses multiple barriers that include the waste form, container, sealing materials, and the host rock.

The deep geological repository would include multiple barriers, including the ceramic fuel itself, the Zircaloy cladding of the used nuclear fuel; a long-lived corrosion-resistant container; clay backfill and other repository seal materials (e.g., shaft seals); and the natural barrier provided by the host rock and surrounding geologic environment.

The multiple barriers would operate together, to contain and isolate the waste, and to prevent, delay and lessen the potential radionuclide releases from the used nuclear fuel. Since more than one barrier acts to either delay the release or slow the movement of radionuclides, the early failure of any one barrier would not compromise the safety of the system. This robustness has been examined in various safety assessments using “what if” scenarios in which a particular barrier is assumed to fail.

7.2.2 Stable Host Rock

Reason 2: The host rock would be stable and predictable over long periods of time.

Scientific investigations during site characterization are expected to show that, for which site is ultimately chosen, conditions at the repository’s depth have been unchanged for millions of years, and therefore have been largely unaffected by surface storms, glaciation, earthquakes, erosion and other natural phenomena over the long timescales that are of relevance to repository safety.

If located in South Bruce, the repository would be in a low seismic hazard area in a stable rock formation. In addition, it is well established from mine experience and basic physical arguments that the mechanical effect of shaking due to earthquakes is less at depth than at surface.

Earthquakes preferentially cause movement along existing fractures. The repository would be located to avoid fractures, so any seismic activity would not directly intersect the repository.

7.2.3 Deep Water Isolated from the Surface

Reason 3: The properties of the host rock would ensure that the waters in the deep rock are isolated and do not readily mix with surface waters.

The repository would be located in a suitable rock formation at a sufficient depth where the conditions are favourable. Favourable conditions could include for example:

- “Tight” rock, which limits groundwater flow.
- Saline (salty) conditions where lighter freshwater sits on top of the heavier saline water, which is a stable arrangement that would tend to reduce any upward groundwater flow. In other words, if saline water is found at depth, that would suggest that those deep groundwaters do not mix with surface waters.
- Groundwater ages (based on scientific analyses) indicating that no mixing with surface waters has occurred, even during the multiple glaciations over the past million years.
- Chemically reducing conditions (“Low-oxygen” conditions), which again indicates that there is no mixing with oxygenated surface waters.

Site investigations performed to date at the site indicated that deep groundwaters were indeed saline.

7.2.4 Favourable Chemical Conditions

Reason 4: The deep geological repository system would maintain a chemical environment that is favourable to the stability and performance of the repository.

A geological repository for used nuclear fuel is located deep underground to ensure that it is isolated from the dynamic natural processes that occur at or near the surface (e.g., oxidation, erosion, and surface waters). By isolating the repository from the surface environment and selecting a site with long term stability, the containers and engineered barrier systems would experience a *slowly* evolving environment. That is, the disturbances caused by the repository and its construction (e.g., thermal heating) would slowly fade away and ambient conditions would prevail.

A feature of deep geologic disposal that the conditions in the surrounding environment are chemically reducing (“low-oxygen”) and saturated, i.e., there is no oxygen and the pores in the rock are full of water. These conditions are favourable to the stability of the engineered materials such as the copper containers and used nuclear fuel. The repository concept is designed to take advantage of these conditions.

7.2.5 Evidence from Natural Analogues

Reason 5: Natural analogues provide evidence that engineered barrier materials are stable for very long periods of time under similar deep geologic conditions.

The long-term stability of engineered barrier materials such as the copper container and the bentonite buffer material can be inferred from the existence of natural copper deposits (e.g., in the Kewanee Peninsula in Michigan), and bentonite clay deposits (e.g., bentonite clay deposits in Wyoming). Studies of these deposits extend the understanding derived from laboratory experiments over much longer time periods. The mere existence of these long-lived deposits suggests that copper and bentonite clay would remain stable for long periods under conditions not very different to those expected in a repository shortly after it reaches saturation.

Similarly, the Cigar Lake uranium ore body in Saskatchewan, for example, can be considered a natural analogue for used uranium dioxide (UO_2) fuel. Geological evidence from Cigar Lake indicates that natural uraninite under reducing conditions remains stable on a time scale over one billion years, with very little uranium dissolving in the groundwater that moves through the deposit. Furthermore, the natural clay surrounding the ore body has been so effective in containing the uranium that there is no indication of the ore deposit at the earth’s surface. Past flooding problems at the Cigar lake uranium mine were due to the mining operations breaching the natural clay barrier at this site.

In analogy with the Cigar Lake deposit, and because conditions in a saturated deep geological repository are expected to be reducing, the used UO_2 fuel should remain stable over the time frame of interest, i.e., one million years. Also, the engineered clay barrier systems should be effective in limiting the movement of radionuclides away from the repository.

7.2.6 Depth Reduces Likelihood of Intrusion

Reason 6: The depth of the repository would be such that future accidental human intrusion into the closed repository would be very unlikely.

The closure plans for the repository are intended to ensure that future generations would remember that the repository is present. These could involve a range of different mechanisms, from active institutional controls, such as ongoing surveillance and enforcement of local planning bylaws, to passive means such as durable site markers, local memory, and placing records in national archives.

At very long times, it is possible that people may forget about the existence of the repository. It is further possible that some future generation could inadvertently excavate into the repository – for example, during exploratory drilling to check for mineral resources. However, the likelihood of such an intrusion would be low because of the depth of the repository and its geologic setting. In particular:

- There is no indication of economically-significant mineral resources at the South Bruce site. There is no groundwater at repository depth, the porewater itself is undrinkable (too salty) and, moreover, the repository would be at a nominal depth of about 500 m (NWMO 2021d) which far exceeds the range of interest for water supplies. Bedrock water wells, for example, do not generally exceed 150 m depth. Thus, it would be very unlikely that wells would be drilled into the repository.
- The repository would be positioned within a region of rock with low permeability (in other words, the rock is “tight”), which would be inconsistent with groundwater resource use.
- The depth of the repository would require specialized drilling equipment and, therefore, any drilling would likely be part of a carefully monitored and controlled exploration performed by technologically advanced people.

7.2.7 Confidence from Similar International Experience

Reason 7: International progress on repository implementation gives assurance that geological disposal is a sound technical solution and provides practical experience.

The concept of containing and isolating used nuclear fuel from the environment by placing it in repositories deep underground was proposed more than 50 years ago and considerable research and development effort has gone into the development of the concept. The progress which has been made in the scientific and technical aspects of geological disposal gives assurance that this is a sound technical solution which is supported by good scientific understanding.

Societal and ethical considerations have also been taken into account in the discussion of long-term management options, and the deep geological repository has also been found to be consistent with general ethical principles.

There is international scientific consensus that deep geological disposal is the best way we know to provide safe management of used nuclear fuel over the hundreds of thousands of years it must be contained and isolated. And, it’s not just a theoretical solution:

- At Finland’s Onkalo repository on Olkiluoto Island, construction is well under way by nuclear waste management firm Posiva Oy. Final disposal is scheduled to start in the mid-2020's.
- In early 2022, the Swedish government gave its approval for the nuclear fuel and waste management company Svensk Kärnbränslehantering AB (SKB) to build an encapsulation plant and repository for used nuclear fuel at Forsmark, in the municipality of Östhammar. Construction is expected to take about 10 years once all the necessary permits have been issued.
- In September, the National Cooperative for the Disposal of Radioactive Waste (Nagra) selected Nördlich Lägern, as the site for a repository for Switzerland’s used nuclear fuel.
- In France, the National Agency for Radioactive Waste Management (ANDRA) has applied for a construction licence for its Cigéo deep geological repository in Meuse/Haute-Marne.

7.2.8 Several Safety Assessment Case Studies

Reason 8: several safety assessment case studies have been performed, and their results indicate that any impacts are likely to be well below recommended dose constraints and natural background dose rates.

The most likely scenario by which radionuclides from a deep geological repository can reach the surface environment in the post-closure phase is by movement through groundwater after container failure. This scenario has been studied in multiple major case studies in Canada: (e.g., AECL, 1994; NWMO 2013; NWMO 2018a). These safety assessments were done for a variety of repository designs and hypothetical sites. For all cases, most radioactivity was trapped within or near the repository and decayed there. The small amounts released into the surface environment from the repository over long times led to a calculated maximum dose rate to someone living on the site well in the future that would be much less than the CNSC annual public dose limit of 1 mSv/y and the Canadian background dose rate of 1.8 mSv/y. Similar results have been found in safety studies by other countries for a wide range of designs and site conditions (see Section 6.3).

Complementary safety indicators, other than the human dose rate, have also been examined. In Canadian and other studies for relevant candidate sites, these safety indicators are also below their reference values, indicating that the impacts of any radionuclides released from the repository would be much smaller than the impacts associated with naturally occurring radionuclides. See for example, the discussion in Section 6.5.

The results of these safety assessments indicate that the estimated long-term radiological impacts from geological disposal of used nuclear fuel would be small.

7.2.9 Use of Proven Technologies

Reason 9: A geological repository can be built and operated safely using proven technologies.

A geological repository at the South Bruce site would be located at a depth of about 650 m below the ground surface. It would be accessed by shafts. The size of the repository would depend on the number of fuel bundles to be accommodated.

Excavation and construction of deep underground openings in rock formations generally do not represent a technical problem. There is much experience in Canada and worldwide in this type of engineering. The main difference from existing mining projects would be the need to understand the effect of the excavation technique on the properties of nearby rock, since this is not usually of importance in, for example, mine construction. Special attention would also need to be paid so that fracture zones that could intersect the repository are avoided or isolated.

A great deal of relevant experience has also come from the construction and operation of Atomic Energy of Canada Limited’s (AECL’s) Underground Research Laboratory in Manitoba from 1984 to 1998. Although not directly comparable, due to differences in waste characteristics, facility design details and/or site conditions, similar international experience has been gained by other countries who are developing underground disposal of radioactive wastes and is shared internationally including experience at:

- the United States Department of Energy's Waste Isolation Pilot Plant (WIPP) operating repository in Carlsbad, United States; this is a repository for defence wastes in an underground salt formation;
- Swedish Nuclear Fuel and Waste Management Company’s (SKB’s) Äspö Hard Rock Laboratory in Forsmark, Sweden;
- Posiva's ONKALO underground facility in Olkiluoto, Finland;
- Andra's Bure underground facility in Meuse-Haute Marne, France;
- Nagra's Mont Terri research facility in Switzerland; and
- Nagra’s Grimsel Test Site in Switzerland.

Each of these underground facilities has its own characteristics. Despite the differences, the operating experience developed in such facilities and in mining operations world-wide is useful for gaining practical experience with the development of underground disposal. For a directly relevant comparison with facilities that handle used CANDU fuel, please see Section 8.1 below.

7.2.10 Radionuclides Decay Over Time

Reason 10: The radionuclides in the used nuclear fuel decay with time.

When used nuclear fuel is removed from a reactor it is highly radioactive. However, the radioactivity of used nuclear fuel constantly decreases with time and the dominant radionuclides contributing to the radioactivity change with time. In particular, the radioactivity of used nuclear fuel decreases to about 0.01 percent of its initial value (i.e., the value when it is removed from the reactor) after about 100 years. After approximately 500 years the radioactivity has decreased a further 10-fold. The radioactivity and radiotoxicity of used nuclear fuel becomes similar to that of naturally occurring uranium ore bodies within approximately one million years.

7.2.11 Monitoring to Confirm Performance

Reason 11: The repository site will be monitored to confirm repository system performance.

The site would be monitored for decades during the licensing, construction and operation process, so there will be a substantial database of information on the deep groundwater system and repository performance before a decision on closure of the repository is made. Site monitoring would be used to establish baseline conditions against which disturbances associated with the repository can be detected, and with which predictions of repository performance can be validated.

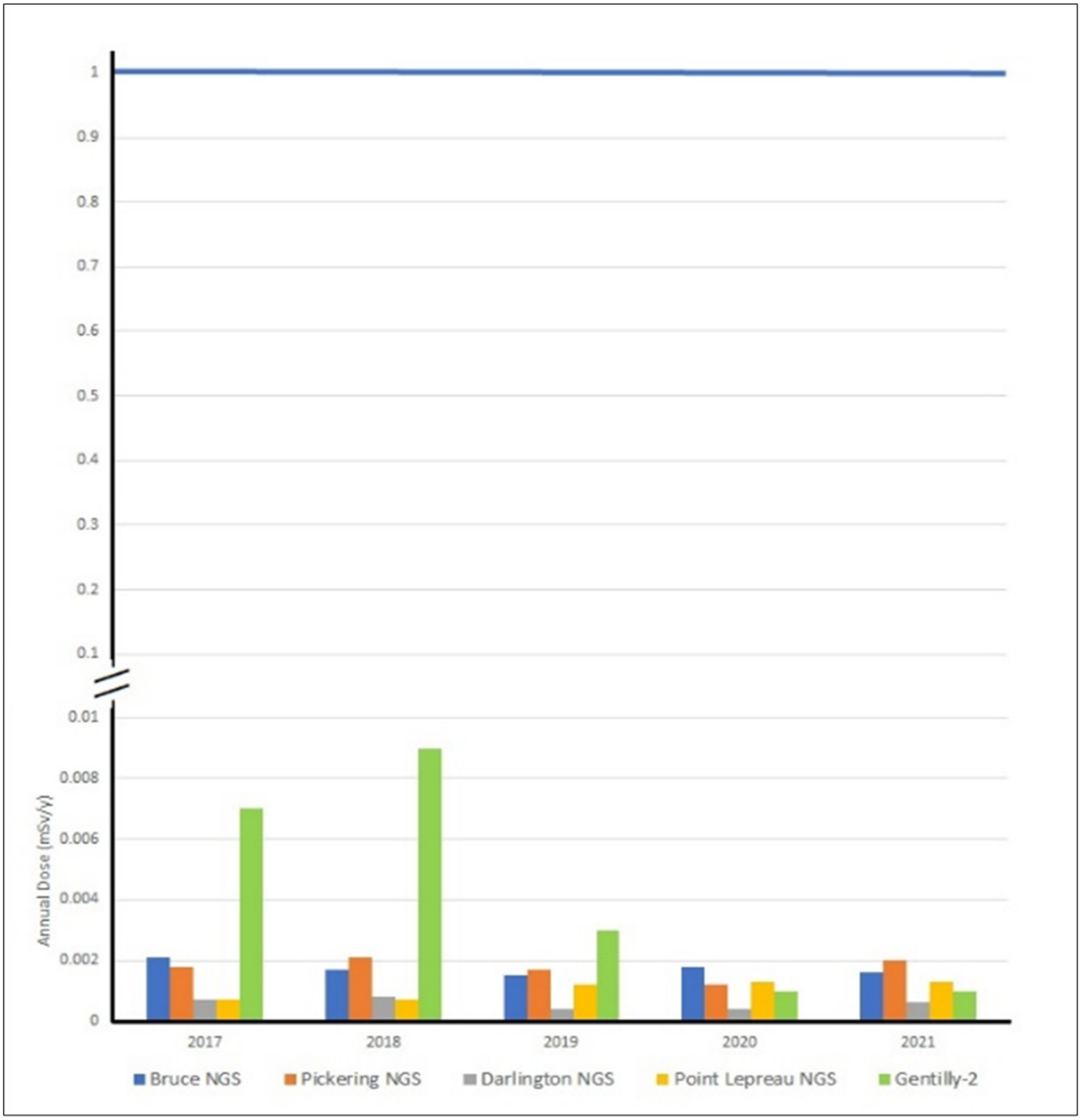
Once all of the Used Fuel Containers have been placed in the repository, the NWMO would continue to monitor long-term safety and performance of the repository system. During this phase, placement rooms would have been sealed-off, but access tunnels would remain open and maintained to support monitoring activities. This extended monitoring phase could last several decades (70 years has been assumed for planning purposes) (NWMO 2021d). The NWMO would have to demonstrate the site’s long-term safety during the extended monitoring phase. The actual duration of this phase would be determined based on society’s desire at the time as well as experience from other international deep geological repositories for used nuclear fuel.

8 Discussion

8.1 Experience with Existing Canadian Nuclear Facilities

In addition to the conservative dose estimates for the operations phase, there are also precedents from actual experience with waste operations of used nuclear fuel. Used nuclear fuel is handled and stored in nuclear power stations in Canada. This used nuclear fuel is fresher (and therefore, more radioactive) than what is planned to be handled in the DGR. The safety performance of these facilities has been excellent. Both the dose rates and emissions from the processing areas have remained below regulatory limits (see CNSC 2020e).

More specifically, the actual dose to the public from nuclear generating stations (including the dose from reactor operation, and from waste handling and storage) is shown in Figure 8-1, in comparison to the CNSC annual dose limit (1 mSv/y). The dose rate from the DGR is expected to be similar or lower (because the DGR facility does not include operating reactors).



Note scale break.

Figure References:

1. Bruce NGS: Bruce Power (2022; 2021), for 2017-2019 CNSC (2020f)
2. Pickering NGS: OPG (2022; 2021), for 2017-2019 CNSC (2020f)
3. Darlington NGS: OPG (2022; 2021), for 2017-2019 CNSC (2020f)
4. Point Lepreau NGS: NB Power (2022; 2021), for 2017-2019 CNSC (2020f)
5. Gentilly-2: Hydro Québec (2022; 2021), for 2017-2019 CNSC (2020f)

Figure 8-1 Dose Rates to Members of the Public from Canadian Nuclear Generating Stations

For additional perspective, the following discussion is reproduced from the CNSC (CNSC 2017), which describes the conclusions drawn from a key 2017 study of doses to populations living near nuclear power plants in Canada:

"The CNSC has completed a groundbreaking ecological study on populations living near Ontario's three nuclear power plants (NPPs). The purpose of the Radiation and Incidence of Cancer Around Ontario Nuclear Power Plants from 1990 to 2008 study (the "RADICON" study) *was to determine the radiation doses to members of the public living within 25 km of the Pickering, Darlington, and Bruce NPPs (Nuclear Power Plants) and to compare cancer cases among these people with the general population of Ontario from 1990 to 2008. The study was conducted using data from the Canadian and Ontario Cancer Registries and the Census of Canada.*

The most important finding of the RADICON study is that there is no evidence of childhood leukemia clusters around the three Ontario NPPs. The rates of cancer incidence for children aged 0–4 and aged 0–14 were similar to the general Ontario population.

Overall, for all ages, there is no consistent pattern of cancer across the populations in question living near the three facilities studied. Some types of cancer in the communities studied were higher than expected (excess cancer); however, many types of cancer were lower than expected.

While this type of study cannot determine the causes of the cancer, excess cancers (increase in cancer above what's expected in Ontario) are unlikely to be due to radiation. Radiation doses from NPPs to members of the public are extremely low – at least 100 to 1,000 times lower than natural background radiation and public dose limits. As such, doses are a minor risk factor compared to the high prevalence of major risk factors like tobacco, poor diet, obesity and physical inactivity, which account for about 60 percent of all cancer deaths in developed countries. These factors represent a public health concern throughout Ontario, including the communities located near NPPs. Other important Ontario studies found that once these main risk factors were taken into account, there was no evidence of a cancer risk due to environmental factors like radiation. Given the high frequency of these factors, the current scientific understanding of radiation risk, and the minuscule public doses, it is not realistic to attribute any excess cancers to the radiation doses from NPPs found in these communities.

To conclude, public radiation doses resulting from the operation of the NPPs are 100 to 1,000 times lower than natural background radiation and there is no evidence of childhood leukemia clusters around the three Ontario NPPs. All cancers for all age groups are well within the natural variation of the disease in Ontario. Thus, radiation is not a plausible explanation for any excess cancers observed within 25 km of any Ontario NPP."

8.2 Confidence in Safety

Confidence in the suitability of the South Bruce Site is based on both intrinsic characteristics of the repository approach, as well as regional geological information and South Bruce site-specific results acquired to date. Safety-related measures and aspects would include:

- Operations Phase:
    - controlled site access;
    - engineering, design, and process controls;
    - modern emissions controls;
    - implementing a robust health & safety program;
    - implementing a robust radiation protection program;
    - regular maintenance of equipment and facilities;
    - establishing emergency preparedness and response measures; and,
    - using monitoring initiatives to verify levels in the environment.
- Post-closure Phase:
    - The favourable characteristics of the geological setting (e.g., the geologic formation has low permeability at depth, no active features, low heterogeneity, very low groundwater flow, and is of a sufficient spatial extent to accommodate the repository);
    - The long-term stability of the geological setting;
    - The low risk of inadvertent future human intrusion into the repository (due to the planned depth, and the fact that there is no indication of economically-significant mineral resources);
    - The site is amendable to geological characterization: in southern Ontario, the lateral homogeneity of the sedimentary rock formations is favorable for predicting the overall host rock structure and characteristics from the available and planned studies;
    - The robustness of the multiple-barrier concept;
    - The ability to safely construct and operate the repository: a preliminary conceptual design has been developed for the repository facilities and is consistent with international best practice. It is presently being adapted to the site-specific conditions;
    - Evidence gained from natural analogues;
    - Confidence gained from similar international projects;
    - Use of proven technologies;
    - Radioactive decay over time; and,
    - Use of monitoring programs to confirm performance.

It is expected that the potential radiological effects of the Project during closure and decommissioning, if any, will be less than - and therefore bounded by - the potential effects during operations.

Finally, the Project would be regulated by the robust regulatory frameworks of the CNSC and the IAAC, as discussed earlier, and an Impact Assessment would be completed for the Project.

Overall, 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 management for Canada’s used nuclear fuel.

9 References

Agence nationale pour la gestion des déchets radioactifs (French National Agency for Radioactive Waste Management) (ANDRA). 2016. *Safety Options Report - Post-Closure Part (DOS-AF)*. ANDRA Report CG-TE-D-NTE-AMOA-SR2-0000-15-0062. France.

Agence nationale pour la gestion des déchets radioactifs (French National Agency for Radioactive Waste Management) (ANDRA). 2005. *Dossier 2005 Argile - Safety Evaluation of a Geological Repository*. ANDRA Report. France.

Atomic Energy Control Board (AECB). 1995. *Canada: Living with Radiation*. Accessed online February 2021. https://inis.iaea.org/collection/NCLCollectionStore/_Public/28/006/28006155.pdf

Atomic Energy of Canada Limited (AECL). 1994. *Environmental Impact Statement on the Concept for Disposal of Canada's Nuclear Fuel Waste*. Atomic Energy of Canada Limited Report, AECL-10711, COG-93-1. Chalk River, Canada.

Becker, D.-A., D. Buhmann, R. Storck, J. Alonso, J.-L. Cormenzana, M. Hugi, F. van Gemert, P. O'Sullivan, A. Laciok, J. Marivoet, X. Sillen, H. Nordman, T. Vieno and M. Niemeyer. 2002. Testing of Safety and Performance Indicators (SPIN). European Commission Report FIKW-CT2000-00081. European Commission.

Bruce Power. 2022. *Environmental Protection Report 2021*. No. B-REP-07000-00014. Rev 000. 1 May. Accessed from: https://www.brucepower.com/wp-content/uploads/2022/05/B-REP-07000-00014.pdf

Bruce Power. 2021. *2020 Environmental Protection Report*. No. B-REP-07000-00013. Rev 000. 1 May. Accessed from:https://www.tcenergy.com/siteassets/pdfs/power/bruce-power/tc-bruce-power-environmental-protection-report-2020.pdf

Canadian Nuclear Safety Commission (CNSC). 2021a. Regulatory Document REGDOC-3.6. Glossary of CNSC Terminology. Canadian Nuclear Safety Commission. Available online: https://nuclearsafety.gc.ca/pubs_catalogue/uploads/REGDOC-3-6-Glossary-of-CNSC-Terminology-eng.pdf

Canadian Nuclear Safety Commission (CNSC). 2021b. *CNSC Processes and Practices - Regulatory Fundamentals*. REGDOC-3.5.3. Version 2. Ottawa, Canada.

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

Canadian Nuclear Safety Commission (CNSC). 2020a. *Fact Sheet: Understanding Radiation*. Ottawa, Canada.

Canadian Nuclear Safety Commission (CNSC). 2020b. *Environmental Protection: Environmental Principles, Assessments and Protection Measures.* REGDOC-2.9.1, Version 1.2. Ottawa, Canada.

Canadian Nuclear Safety Commission (CNSC). 2020c. *Fact Sheet: Natural Background Radiation*. November. Accessed from: https://nuclearsafety.gc.ca/eng/pdfs/Fact_Sheets/Fact-Sheet-Background-Radiation-eng.pdf.

Canadian Nuclear Safety Commission (CNSC). 2020d. *Radiation Doses*. December. Accessed from: http://nuclearsafety.gc.ca/eng/resources/radiation/introduction-to-radiation/radiation-doses.cfm

Canadian Nuclear Safety Commission (CNSC). 2020e. *Seventh Canadian National Report for the Joint Convention*. Accessed from: https://nuclearsafety.gc.ca/eng/resources/publications/reports/jointconvention/seventh-report/seventh-report-joint-convention.cfm

Canadian Nuclear Safety Commission (CNSC). 2020f. *Regulatory Oversight Report for Nuclear Power Generating Sites: 2019.* Accessed from: http://nuclearsafety.gc.ca/eng/resources/publications/reports/regulatory-oversight-reports/npgs-report-2019.cfm

Canadian Nuclear Safety Commission (CNSC). 2019a. *Atoms – Nuclides and Radioisotopes*. September. Accessed in January 2021 from https://nuclearsafety.gc.ca/eng/resources/radiation/introduction-to-radiation/atoms-nuclides-radioisotopes.cfm

Canadian Nuclear Safety Commission (CNSC). 2019b. *Radiation Health Effects*. September. Accessed in March 2021 from http://nuclearsafety.gc.ca/eng/resources/radiation/introduction-to-radiation/radiation-health-effects.cfm

Canadian Nuclear Safety Commission (CNSC). 2018. *Radionuclide Information Booklet*. April. Available at: http://www.nuclearsafety.gc.ca/pubs_catalogue/uploads/Radionuclide-Information-Booklet-2018-eng.pdf

Canadian Nuclear Safety Commission (CNSC). 2017. *Radiation and Incidence of Cancer Around Ontario Nuclear Power Plants from 1990 to 2008 (The RADICON Study)*. September. Accessed in March 2021. https://nuclearsafety.gc.ca/eng/resources/health/health-studies/radicon-study.cfm

Canadian Nuclear Safety Commission (CNSC). 2014a. *Our Mission*. March. Accessed in January 2021 from http://nuclearsafety.gc.ca/eng/about-us/our-mission.cfm

Canadian Nuclear Safety Commission (CNSC). 2014b. *Deterministic Safety Analysis*. REGDOC-2.4.1. Ottawa, Canada.

Canadian Standard Association (CSA). 2012. *CSA N288.6-12 Environmental Risk Assessments at Class I Nuclear Facilities and Uranium Mines and Mills*. Toronto, Canada.

DPRA Canada Inc. and Independent Environmental Consultants Inc. (DPRA & IEC). 2022. *Emergency Services Study Report – Southwestern Ontario Community Study*. Prepared for the Nuclear Waste Management Organization. Toronto, Canada.

Garisto, F., J. Avis, N. Calder, A. D’Anrea, P. Gierszewski, C. Kitson, T. Melnyk, K. Wei and L. Wojciechowski. 2004. *Third Case Study – Defective Container Scenario*. Ontario Power Generation Report No. 06819-REP-01200-10126-R00. Toronto, Canada.

Grasty, R.L. and LaMarre, J.R. 2004. *The Annual Effective Dose from Natural Sources of Ionizing Radiation in Canada*. Radiation Protection Dosimetry 108: 215-226.

Health Canada. 2020. *Radiation Protection Bureau*. Accessed in March 2021. https://www.canada.ca/en/health-canada/corporate/about-health-canada/branches-agencies/healthy-environments-consumer-safety-branch/environmental-radiation-health-sciences-directorate/radiation-protection-bureau.html

Hydro Québec. 2022. *Résultats de la surveillance de l'environnement des installations de Gentilly-2. Rapport annuel 2021.* No. G2-RT-2022-00518-001. Version finale. April. Accessed from: https://www.hydroquebec.com/data/production/pdf/rapport-surveillance-environnement-gentilly-2021.pdf

Hydro Québec. 2021. *Résultats de la surveillance de l'environnement des installations de Gentilly-2. Rapport annuel 2020.* No. G2-RT-2021-00518-001. Version finale. April. Accessed from: https://www.hydroquebec.com/data/production/pdf/rapport-surveillance-environnement-gentilly-2020.pdf

Impact Assessment Agency of Canada (IAAC). 2020. *Impact Assessment Agency of Canada – Mandate*. Accessed in March 2021. https://www.canada.ca/en/impact-assessment-agency/corporate/mandate.html

International Atomic Energy Agency (IAEA). 2019. *IAEA Safety Glossary: Terminology Used in Nuclear Safety and Radiation Protection, 2018 Edition*. STI/PUB/1830. Vienna. June. Accessed from https://www.iaea.org/publications/11098/iaea-safety-glossary-2018-edition

International Atomic Energy Agency (IAEA). 2016*. An International Peer Review of the Safety Options Dossier of the Project for Disposal of Radioactive Waste in Deep Geological Formations (Cigéo)*. Final Report of the IAEA International Review Team. Vienna, Austria.

International Atomic Energy Agency (IAEA). 2004. *Radiation, People and the Environment - A Broad Overview of Ionizing Radiation, Its Effects and Uses, as well as the Measures in Place to use it Safely*. February. Accessed March 2021. https://www.iaea.org/sites/default/files/radiation0204.pdf

International Atomic Energy Agency (IAEA). 1999. *Basic Safety Principles for Nuclear Power Plants.* No. 75-INSAG-3 Rev 1 INSAG-12. Report by the International Nuclear Safety Advisory Group.

International Commission on Radiological Protection (ICRP). 2007. *Annals of the ICRP – The 2007 Recommendations of the International Commission on Radiological Protection*. ICRP Publication #103. ISBN No. 978-0-7020-3048-2. March.

JNC. 2000. *H12: Project to Establish the Scientific and Technical Basis for HLW Disposal in Japan - Supporting Report 3 – Safety Assessment of the Geological Disposal System*. Japan Nuclear Cycle Development Institute. JNC TN1410 2000-004. Japan.

Kremer, E.P and Garisto, N.C. 2011. *Dose Considerations for A Site Boundary for Surface Operations At A Deep Geological Repository.* APM-REF-01917-26229.

Municipality of South Bruce (MSB). 2020. South Bruce Guiding Principles for NWMO's Site Selection Process. Accessed online 04July2023: https://www.southbruce.ca/en/A-PDF-Forms/Nuclear/Revised-36-Principles-with-New-Comms-Contact.pdf

Nagra. 2002. *Project Opalinus Clay: Safety Report. Demonstration of Disposal Feasibility for Spent Fuel, Vitrified High-Level Waste and Long-Lived Intermediate-Level Waste (Entsorgungsnachweis).* Nagra Technical Report. Switzerland.

Natural Resources Canada (NRCan). 2017. *Natural Resources Canada - Nuclear Energy*. Accessed in March 2021.https://www.nrcan.gc.ca/energy/energy-sources-distribution/uranium-nuclear-energy/nuclear-energy/7711

New Brunswick Power (NB Power). 2022. *Point Lepreau Nuclear Generating Station Annual Compliance Report. Annual Report on Environmental Protection – 2021*. No. ACR-07000-2021 Rev.0. April. Accessed from: https://www.nbpower.com/media/1492079/annual-report_on_environmental-protection_2021.pdf

New Brunswick Power (NB Power). 2021. *Point Lepreau Nuclear Generating Station Annual Compliance Report. Annual Report on Environmental Protection – 2020*. No. ACR-07000-2020 Rev.0. April. Accessed from: https://www.nbpower.com/media/1491306/0087-07000-2020-001-acr-a-00.pdf

Nuclear Waste Management Organization (NWMO). 2022. *Confidence in Safety – South Bruce Site*. NWMO No. NWMO-TR-2022-15. R000. Toronto, Canada.

Nuclear Waste Management Organization (NWMO). 2021a. *APM Deep Geological Repository - Project Glossary*. APM-LIST-00120-001. Rev. 4. Toronto, Canada.

Nuclear Waste Management Organization (NWMO). 2021b. *CNSC Commission Member Document (CMD). Implementation of Adaptive Phased Management*. CMD: 21-M17.1. Reference CMDs: 17-M50.1. April.

Nuclear Waste Management Organization (NWMO). 2021c. *Website: How Is It Stored Today*. Accessed on April 2021 from https://www.nwmo.ca/en/Canadas-Plan/Canadas-Used-Nuclear-Fuel/How-Is-It-Stored-Today.

Nuclear Waste Management Organization (NWMO). 2021d. *Deep Geological Repository Conceptual Design Report Crystalline / Sedimentary Rock*. NWMO No. APM-REP-00440-0211-R000. Toronto, Canada.

Nuclear Waste Management Organization (NWMO). 2020. *Preliminary Radon Assessment for a Used Fuel Deep Geological Repository.* NWMO-TR-2019-09. Toronto, Canada.

Nuclear Waste Management Organization (NWMO). 2018a. *Postclosure Safety Assessment of a Used Fuel Repository in Sedimentary Rock*. NWMO No. NWMO-TR-2018-08. Toronto, Canada.

Nuclear Waste Management Organization (NWMO). 2018b. *7th Case Study: Reference Data and Codes*. NWMO No. NWMO-TR-2018-10. Toronto, Canada.

Nuclear Waste Management Organization (NWMO). 2017. *Postclosure Safety Assessment of a Used Fuel Repository in Crystalline Rock*. NWMO No. NWMO TR-2017-02. Toronto, Canada.

Nuclear Waste Management Organization (NWMO). 2016a. *APM DGR Preliminary Description*. NWMO No. APM-REP-06415-0201. R000. Toronto, Canada.

Nuclear Waste Management Organization (NWMO). 2016b. *Deep Geological Repository Conceptual Design Report Crystalline / Sedimentary Rock Environment*. NWMO No. APM-REP-00440-0015. R001. Toronto, Canada.

Nuclear Waste Management Organization (NWMO). 2013. *Postclosure Safety Assessment of a Used Fuel Repository in Sedimentary Rock*. NWMO No. NWMO TR-2013-07. Toronto, Canada.

Nuclear Waste Management Organization (NWMO). 2012. *Used Fuel Repository Conceptual Design and Postclosure Safety Assessment in Crystalline Rock: Pre-Project Report*. NWMO No. NWMO TR-2012-16. Toronto, Canada.

Nuclear Waste Management Organization (NWMO). 2009. *Technical Summary of the Safety Aspects of the Deep Geological Repository Concept for Used Nuclear Fuel*. NWMO No. NWMO TR-2009-12. Toronto, Canada.

Nuclear Waste Management Organization of Japan (NUMO) 2021. The NUMO Pre-siting SDM-based Safety Case. NUMO-TR-21-01. Tokyo, Japan. Accessed from: https://www.numo.or.jp/technology/technical_report/pdf/NUMO-TR21-01_rev220222.pdf

Ontario Power Generation (OPG). 2022. *2021 Results of Environmental Monitoring Programs.* OPG No. N-REP-03443-10027. April. Accessed from: https://www.opg.com/documents/2021-environmental-monitoring-program-report/

Ontario Power Generation (OPG). 2021. *2020 Results of Environmental Monitoring Programs.* OPG No. N-REP-03443-10026. April. Accessed from: https://www.opg.com/documents/environmental-monitoring-program-2020-report/

Posiva. 2021. *Website: Final Disposal*. Accessed from: https://www.posiva.fi/en/index/finaldisposal/researchandfinaldisposalfacilitiesatonkalo.html. April 2021.

Posiva 2012. *Safety case for the disposal of spent nuclear fuel at Olkiluoto – Synthesis 2012*. POSIVA 2012-12, Eurajoki, Finland: Posiva Oy 277 p.

Posiva. 2007. Safety assessment for a KBS-3H Spent Nuclear Fuel Repository at Olkiluoto, Summary Report. Posiva Report 2007-06. Finland.

Svensk Kärnbränslehantering (Swedish Nuclear Fuel and Waste Management Company) (SKB). 2011a. *Environmental Impact Statement: Interim Storage, Encapsulation and Final Disposal of Spent Nuclear Fuel.* March. Accessed from: https://skb.se/wp-content/uploads/2016/01/A-EIS_2011.pdf. October.

Svensk Kärnbränslehantering (Swedish Nuclear Fuel and Waste Management Company) (SKB). 2011b. *Long-term Safety for the Final Repository for Spent Nuclear Fuel at Forsmark. Main Report of the SR-Site Project*. Volumes I and II. SKB Technical Report TR-11-01. Sweden.

The United Nations Scientific Community on the Effects of Atomic Radiation (UNSCEAR). 2020. *Sources, Effects and Risks of Ionizing Radiation – USCEAR 2019 Report – Report to the General Assembly, with Scientific Annexes*. ISBN no. 978-92-1-139184-8. December.

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). 2010. *Sources and Effects of Ionizing Radiation.* UNSCEAR 2008 Report to the General Assembly, With Scientific Annexes. ISBN 978-92-1-142274-0. United Nations, New York, USA.

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). 2000. *Sources and Effects of Ionizing Radiation.* UNSCEAR 2000 Report to the General Assembly, With Scientific Annexes. ISBN 92-1-142238-8. United Nations, New York, USA.

World Health Organization (WHO). 2017. *Guidelines for Drinking-Water Quality: Fourth Edition Incorporating the First Addendum*. Geneva, Switzerland.

Arcadis Canada Inc.
121 Granton Drive, Suite 12
Richmond Hill
Ontario L4B 3N4
Phone: 905 764 9380
www.arcadis.com