Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

Assessment Document

PERFORMANCE ASSESSMENT FOR NEAR SURFACE DISPOSAL FACILITY - 100% DESIGN

232-509240-ASD-001

Revision 1

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Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

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Near Surface Disposal Facility (NSDF) Project

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1. INTRODUCTION

The Performance Assessment (PA) is based on the 100% design submitted 2017 April.

1.1 Background

1.1.1 Chalk River Laboratories

Canadian Nuclear Laboratories (CNL) operates Chalk River Laboratories (CRL), a nuclear research facility located in Renfrew County, in the Province of Ontario, Canada.

Operations have been ongoing at CRL since the 1940's and are expected to continue for many more decades. Operations at CRL are carried out subject to the Nuclear Research and Testing Establishment Licence [1-1] (i.e. the CRL Site Licence) that is issued by the Canadian Nuclear Safety Commission (CNSC). The licence is subject to periodic review and renewal, in accordance with regulations and processes that are defined by the CNSC.

Approximately 2600 of CNL's 3000 employees work at the CRL site. They are engaged in a wide variety of scientific and engineering research and development (R&D) work. General areas of work include R&D in support of:

- CANDU® power reactors, as well as medical and industrial applications of radiation and radioactive isotopes.
- The biological and environmental effects and behaviour of radiation and radioactive materials.
- Radioactive waste management.

In addition to R&D, CRL also provides radioactive waste management services for CNL facilities and for Canadian hospitals, universities and industries. Fuel for research reactors is also manufactured at CRL.

The aforementioned work is conducted in laboratories and various operational facilities at the CRL site. Support facilities (Powerhouse, various workshops, maintenance shops, etc.) and utilities (e.g. electricity, steam, water, natural gas, communications, etc.) enable all of the work.

The Waste Management Areas (WMAs) are central to the management of radioactive waste. The WMAs are identified as a licensed facility on the CRL Site Licence and are located on the CRL property along the southwest to northeast corridor formed by the main road (Plant Road) leading from the Village of Chalk River to the Built-p Area (i.e. CRL main campus). The active waste areas have controlled access. Section 1.8 of this report provides further information about the WMAs.

1.1.2 Near Surface Disposal Facility

Canadian Nuclear Laboratories is planning to undertake a new Near Surface Disposal Facility (NSDF) Project at CRL for the safe and permanent disposal of solid radioactive waste. The Project includes the work to design, licence, construct, commission, operate, close, decommission and monitor the new facility.

The NSDF will consist of an engineered containment mound (ECM) to dispose of the waste, a Waste Water Treatment Plant (WWTP) to treat leachate generated in the ECM and small wastewater streams generated by NSDF supporting facilities, and various site infrastructure, including roads and services that are required to operate the NSDF.

At the next cycle of the CRL site licence renewal, CNL will seek to include the NSDF within the WMAs. This performance assessment addresses activities which would be conducted under the terms of the licence issued by the Canadian Nuclear Safety Commission (CNSC) for the WMA and is designed to satisfy the following, but is not limited to:

- The requirements of the *General Nuclear Safety and Control Regulations*, including Section 3 (1)(i) for a description of the results of any test, analysis or calculation performed to substantiate the information included in the application.
- The requirements for CNSC document *P-290 Managing Nuclear Waste*.
- The requirements of CNSC regulatory guideline document *G-320 Assessing the Long-term Safety of Radioactive Waste Management*.
- The guidance specified by the IAEA, including those in SSG-23 [1-2] and SSG-29 [1-3].

1.2 Objectives and Scope

An Environmental Assessment (EA) has been undertaken to minimize or avoid potential adverse environmental effects and incorporate environmental factors into decision making. Furthermore, demonstration of a long-term safety is a requirement for the disposal of radioactive waste in Canada [1-4].

The overall objective is to assess the potential long-term impact that radioactive waste disposal may have on the environment and on human health and safety [1-4].

This Performance Assessment (PA) is developed to support the NSDF's Environmental Impact Statement (EIS). The EIS is a document that summarizes the EA process and demonstrates the effects of the project on the environment, humans, and non-human biota. The scope of this PA is to:

- Quantify short-term and long-term radiological impacts on humans and the environment in support of the EA.
- Consider normal operations and accidents.
- Provide PA input into:
    - Final design
    - Waste Acceptance Criteria (WAC)
    - Safety Analysis

Further analysis will be presented in the Safety Analysis Report (SAR) and in follow-up addendums.

The PA Report for the NSDF does not include:

- Conventional (non-radiological) safety assessment.
- Assessment of consequences due to emissions of hazardous wastes and substances.
- Design options analysis
- As Low As Reasonably Achievable (ALARA) assessment.

These analyses are provided in the Environmental Impact Statement [1-5], and the Safety Analysis Report (SAR, which has been prepared separately based on the 100% design).

1.3 Project-Related Document Relationships

Canadian Nuclear Laboratories has initiated a Project to design, build, operate, close and decommission a new facility – the NSDF - to safely dispose of radioactive wastes from a variety of sources; including legacy waste, operational waste, decommissioning waste, and future waste streams. CNL is implementing the NSDF Project on a high priority basis and has engaged its own project resources and those of engineering and environmental consulting firms. Several related activities, including analyses and report preparation, are being performed in parallel and involve close interaction between and among these resources.

Four documents, in particular, are closely related and contain a degree of overlap in their supporting analyses and content: the PA (i.e. this document), the EIS, the SAR and the Waste Acceptance Criteria (WAC). While each of these is described more fully below, in general terms, the EIS is performed to assess feasibility, and to determine what the effects of the project on the environment will be. The PA is an important input to the EIS. The SAR assesses the safety of the final design of the facility. The WAC describes the kind of waste the facility will accept for disposal, including limits and requirements on radioactivity concentration, chemical forms, physical forms, hazardous forms, etc.

The interactions between these reports and supporting analyses are described, as follows:

Performance Assessment: The PA assesses the dose consequences from both the pre-closure and post-closure periods of the NSDF lifecycle (see Section 1.7), including the period beyond institutional control.

The PA is prepared in parallel with the design of the facility, and is produced to support and inform the EIS. The PA uses a reference waste inventory (see Section 4) to analyze the normal evolution of the facility through its lifecycle, as well as disruptive events, such as accidents and extreme weather conditions. The PA's major focus is the long-term assessment of the ECM that encapsulates the waste and the worst-case scenario(s) (arising from, for example, disruptive events) which result in the highest dose to the worker, public, or biota.

Worst-case scenario(s) and benchmarking exercises against other facilities inform the maximum allowable concentrations of radionuclides that can safely be disposed of in the facility. This information informs the WAC, the design for the ECM and WWTP, as well as the radioactive source terms used in the SAR.

As the design developed, both from the initial PA analyses outputs and as part of normal design progression, the PA models were updated and re-run to reflect the maturing elements of the design and WAC information. As such, the development of the PA, WAC, and the design of the facility was an iterative and interactive process.

The main differences between the prior draft PA and the present 100% design PA are:

- The use of updated engineering design parameters (see Section 6); and,
- The use of an updated inventory (see Section 4).

Environmental Impact Statement: The purpose of the EIS is to determine the potential effects of the project on the environment, including terrestrial and aquatic life, air and water, the public, indigenous and metis communities, as well as studying the socio-economic effect of the project. Additionally, the EIS assesses how the environment may impact the project, i.e., climate change, natural disasters, etc. The EIS identifies mitigation measures to address potential adverse effects.

The EIS for the NSDF is prepared in parallel with the facility design, PA, and safety assessment. Like the PA, the EIS relies heavily on the information available up to and including the 100% design. The EIS covers the entire lifecycle of the facility, from site preparation to beyond the end of institutional control. The EIS includes sections which assess dose consequences to the public, workers, and to biota, from normal operations and accident scenarios. Much of this information is produced in the PA, and referenced in the EIS.

Safety Analysis Report: The purpose of the SAR is to study and analyze the overall safety of the facility for all phases of the project. The analysis in the SAR is used to determine if there are Safety Related Systems in the design of the project.

The SAR is prepared in parallel with the facility design. The final SAR is representative of the 100% design. The SAR analyses the stages of the project involving radioactive sources, i.e., Operations, Closure, and Post-Closure periods. Scenarios assessed in the PA may be applicable to the SAR provided that no assumptions or design elements pertinent to the PA were changed post completion of the EIS. In these cases, the SAR references the PA and conclusions within the PA document.

Waste Acceptance Criteria: The WAC is a set of limits and requirements that define the waste that will be accepted for disposal in the new facility. The WAC imposes limits on waste properties, such as the physical form, chemical form, weight, size, hazardous constituents, etc. Of particular importance for the NSDF, the WAC puts limits on radioactivity concentration and total radioactive inventory of specific radionuclides. The radioactivity limits are based on results of the PA, in order to ensure that even the worst-case scenarios do not result in significant adverse effects on the public or the environment. The WAC is finalized with the final 100% design of the NSDF.

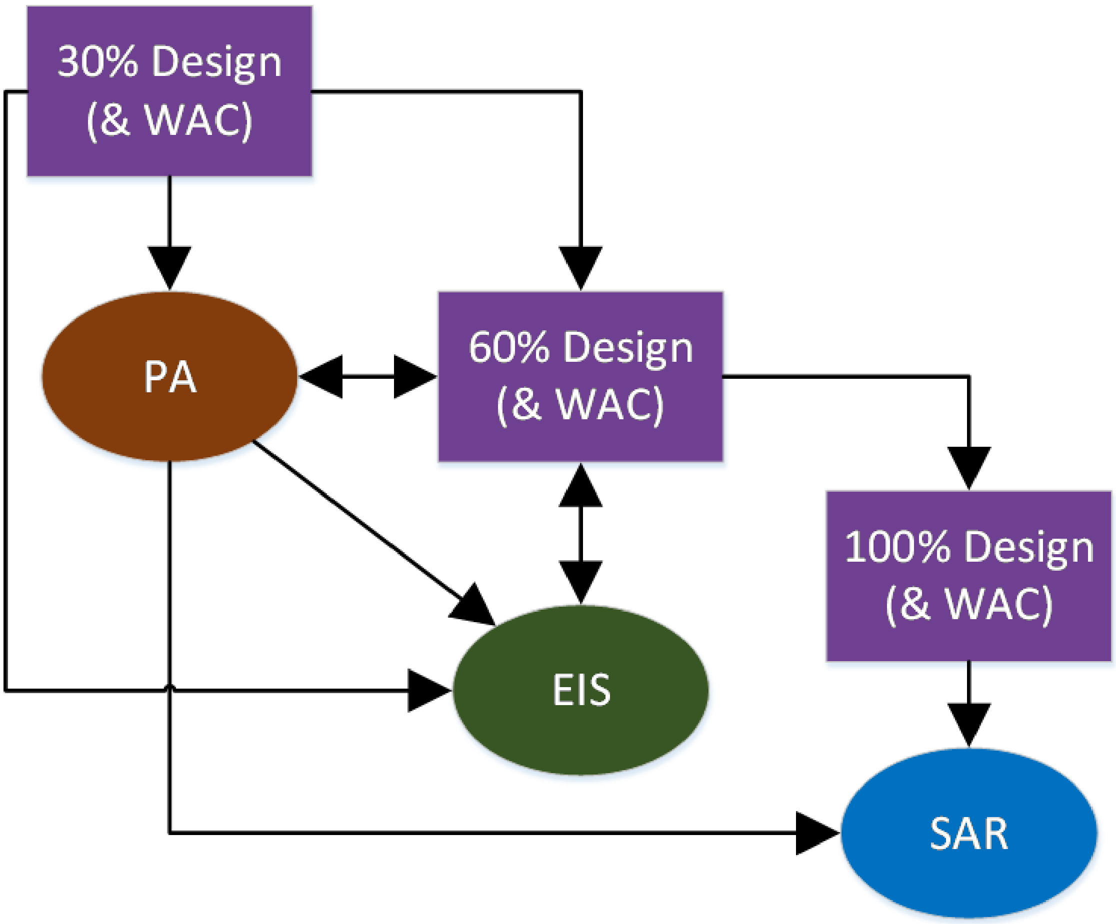

Figure 1-1 Project Related Document Relationships

1.4 Structure of Report

The structure of the report is as follows:

- Section 1 specifies project scope and objectives, provides an overview of the general approach to selection of the appropriate methodology, describes timeframes, adjacent facilities, and Quality Assurance.
- Section 2 defines the safety objective and safety criteria for normal operations and accidents or disruptive events.
- Section 3 describes site characteristics, which are relevant to this assessment.
- Section 4 provides radiological inventory and information on WAC.
- Section 5 describes the proposed concept for operating the NSDF.
- Section 6 summarizes principal design features, available at the time of writing.
- Section 7 provides preliminary pre-closure assessment and defines potential failures and disruptive events, some of which relate to post-closure analysis.

- Section 8 presents bounding and scoping assessment for normal evolution and disruptive scenarios which may take place during post-closure.
- Section 9 describes operational programs.
- Section 10 provides an overall conclusion and describes how the safety objectives will be met.

The elements of long-term assessment, specified in the CNSC Guidance [1-4], are addressed throughout the document, as summarized in Table 1-1.

Table 1-1 Alignment with CNSC Guidance [1-4]

Assessment Element	Section
1. Selection of appropriate methodology	Sections 1.4 (General Approach), 7 (Methodology for Pre-closure period) and 8 (Methodology for Post-closure period)
2. Assessment context	Section 1 (Describes why the assessment is being conducted).
3. System description	Sections 3 (Site Characteristics), 4 (Waste acceptance criteria and inventory), 5.2 (Operations) and 6 (Design Features).
4. Time frames	Section 1.7 (Lifecycle).
5. Assessment scenarios	Section 7 (Pre-closure) and Section 8 (Post-closure).
6. Development of assessment models	Section 7 (Pre-closure) and Section 8 (Post-closure).

1.5 General Approach

This section describes the general approach and generic assumptions common to the overall analysis implemented within this PA. Methods and assumptions, which are specific to individual calculations, are described in the respective sections of this report.

In order to determine whether or not the project can be carried out, a scoping and bounding methodology was used, as is generally done at the EA stage. A scoping and bounding methodology uses conservative values and cases that are representative of the worst case to ensure that the effects of the project will be acceptable. This assessment will ensure that the project can be carried out from initial construction through to the final closure and decommissioning, within an acceptable safety envelope. Once the EIS has demonstrated that the project can be carried out in an acceptably safe manner, final *detailed* engineering can be completed to put the concepts into practice and optimize the design. This will be supported by the safety analysis (documented in the SAR) and demonstrate that all phases of the Project will be implemented in a safe manner. In contrast, the PA’s parallel development began during earlier phases of the design and therefore relies on bounding and scoping calculation methods to demonstrate feasibility of the project.

The overall purpose of PAs for radioactive waste disposal facilities is to evaluate the long-term safety of the disposal facility. This is achieved by adopting [1-4]:

1. Nationally and internationally accepted best practices, and.
2. Presenting the 'weight of evidence' and confidence-building arguments (i.e. scientific evidence, multiple lines of reasoning, reasoned arguments, and other complementary arguments) that support the assessment and its conclusions.

A comprehensive approach for performing PAs for near surface facilities was developed by the International Atomic Energy Agency (IAEA) under its Research Coordinated Project on Improvement of Safety Assessment Methodologies (ISAM) [1-6]. This approach has been adopted to develop the PA for the NSDF, as follows:

- Application of multiple lines of reasoning, such as radionuclide fluxes and concentrations to complement assessed doses.
- Adoption of conservative and bounding, rather than "realistic" assumptions to account for uncertainties in the inventory and future evolution of the system and environment.
- Assessment time frames include pre- and post-closure phases to ensure protection of current and future generations. The post-closure period will start in 2100 and will include Active and Passive Institutional Control and post-Institutional Control periods. The post-closure analysis focuses on the assessment of the period after the end of Institutional Control until the time when radiological inventory decays to levels of radioactivity naturally present in the environment.
- Assessment scenarios have been designed with consideration of Features, Events and Processes (FEP) [1-7], determined by evaluating comprehensive FEPs databases, designed for near-surface disposal facilities [1-6].
- Conceptual models were established to represent each plausible assessment scenario. These conceptual models formed the basis of mathematical models, which were developed using qualified software packages, which have been validated for this type of analysis and are compliant with the appropriate standards.
- The results have been compared with the appropriate safety criteria, taking into account uncertainty. When required, sensitivity analysis was carried out to evaluate scenario and parameter uncertainty and demonstrate robustness of the disposal system.

As illustrated in Figure 1-2, completing the PA for a radioactive waste disposal facility is an iterative process. Initial assessments may be based on a broad range of site data if NSDF site-specific information is not fully available. Similarly, assumptions relating to design and waste characteristics must be made, for the assessment to develop in parallel with design. Once additional NSDF site-specific data and design information become available, the assessment is revised, as required. Furthermore, the WAC and elements of design may be modified based on the PA results, which may, in turn, require another iteration of analyses, using refined waste inventory and design information.

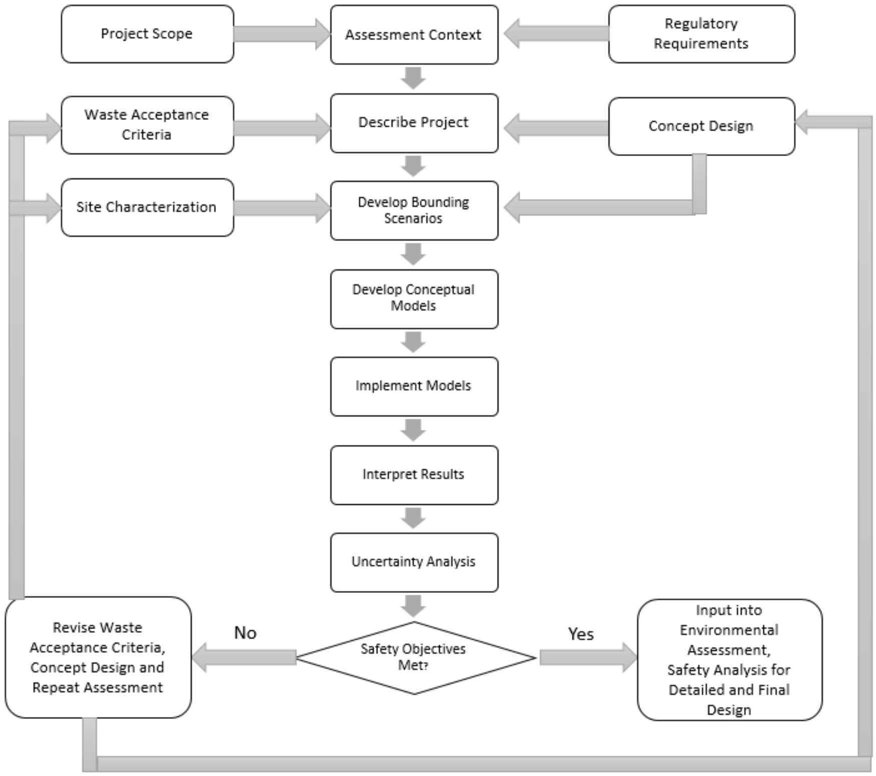

Figure 1-2 Performance Assessment Process (Based on [1-3])

The prediction of hydrogeological and other environmental processes, occurring over long periods of time, is always associated with a degree of uncertainty. Therefore, reasonable assurances of the performance must be provided to account for the uncertainty. This is achieved by beginning with bounding conservatism to ensure that uncertainty lies in the direction of greater safety. Depending on these initial findings, it may be possible to reduce the initial level of conservatism by obtaining additional NSDF site-specific data, enhancing the analysis itself, or making the design more robust.

The resulting inventory and design modifications are then incorporated into subsequent PA revisions. The current iteration of the PA is the final PA iteration, based on the 100% design and conservative assumptions.

1.6 Facility Overview

The NSDF is a radioactive waste disposal facility in the form of an engineered containment mound [1-8],[1-9]. Figure 1-3 illustrates the proposed facility layout. It is similar in design to other landfill-styled waste facilities, and in particular, resembles those under construction at Port Hope and Port Granby under the Port Hope Area Initiative (PHAI). Several facilities with a similar purpose have been constructed and operated on US Department of Energy sites; e.g. Idaho CERCLA Disposal Facility and the Oak Ridge Environmental Management Waste

Management Facility. International near surface disposal facilities include the Low Level Waste Repository (UK) and Centre de l'Aube for Low and Intermediate Level Waste (France). The design features are discussed in Section 6.2, with further details available in the design document [1-8].

The NSDF is comprised of four main, physical elements: the ECM that will contain the waste, the WWTP, operational support facilities and site infrastructure.

The ECM will consist of multiple disposal cells and include the following systems:

- Base liner system.
- Surface water management system.
- Final cover system.
- Passive environmental monitoring systems.

The base liner system includes a primary and secondary liner to limit the potential release of contaminated water (i.e. leachate) to the subsurface and groundwater. In keeping with the defence-in-depth principle, this lining system consists of redundant primary and secondary liner systems, with each component system containing both natural and synthetic barriers. The primary liner will contain the leachate collection system, which will control the accumulation of leachate on the base liner system and convey leachate to sumps external to the ECM. The secondary liner will contain the leak detection system that will be used to detect leaks in the unlikely event that the primary liner system fails and convey leachate to sumps external to the ECM. Additionally, there is a compacted natural clay layer below the secondary liner system, which would retard infiltration in the highly unlikely scenario that leachate penetrated both the first and second liner systems. The surface water management system will control clean surface water on-site, while preventing contact with contaminated areas. The final cover system (i.e. cap for the mound) will be designed to eliminate human exposure due to direct contact with waste, and provide protection from external exposure. The cover will also limit the infiltration of precipitation to the waste, thereby, minimizing leachate generation. The environmental monitoring systems will monitor air, surface water and groundwater consistent with existing CRL licence requirements, and other regulatory requirements.

The WWTP will be required to treat leachate removed from the ECM, as well as wastewater from the NSDF Project's supporting operations. Additionally, any water (e.g. precipitation) that contacts the waste during its emplacement (referred to as contact water) will also be treated to ensure that no contamination is being released in an uncontrolled manner. The WWTP will treat leachate and wastewater ensuring that they meet discharge criteria prior to transfer to an approved discharge location.

The supporting operational facilities includes the vehicle decontamination facility, the office and change room, security kiosk and weigh scales. Site infrastructure includes roads and parking, utilities and material laydown/stockpile areas and surface water management ponds.

Figure 1-3 Illustrative Layout of the Near Surface Disposal Facility

Note: see Figure 6-2 and Figure 6-3 *for the layout of the base liner and cover systems respectively*

1.7 Near Surface Disposal Facility Lifecycle

Canadian Nuclear Laboratories aims to complete the construction of the NSDF, and pass it over to CRL Waste Operations for the commencement of active commissioning in 2020. Development of the NSDF Project is planned in several phases. The site preparation and construction stage is anticipated to start in 2018 or as soon as the relevant regulatory permits and approvals are in place. The operations stage is anticipated to begin in 2020 and will end in approximately 2070 (i.e. operating site life of 50 years). Closure activities following operations, will overlap with post-closure activities and include those necessary to complete the installation of the final cover. Post-closure and monitoring activities, such as groundwater monitoring, extend into the post-closure stage (beyond 2070 and into the period of Institutional Control).

The project consists of the following phases:

- Construction Phase (including site preparation) (2018 - 2020).
- Operating period (2020 - 2070).
- Decommissioning and monitoring activities (2070 - 2100).
- Active and passive Institutional Control (2100 - 2400).
- Post-Institutional Control period (2400 – onwards).

For the purposes of the PA, these phases can be grouped into two categories:

1. Pre-closure

   All phases up until the end of the Closure and Monitoring Activities in 2100.

2. Post-closure

   This period will start in 2100 and will include Active and Passive Institutional Control and post-Institutional Control periods.

Figure 1-4 shows the Project timeline, as well as what documents assess each stage. Figure 1-5 illustrates the approximate time periods and the expected performance of the facility over a period of time, extending to hundreds or even thousands of years.

Prior to the start of Institutional Control, there is no direct interaction between leachate from the ECM and the environment, as all leachate produced will be treated. Leaks, although unlikely due to the multiple engineered barriers, will be detected, through monitoring, and mitigation measures will be put into place to ensure that the environment is protected.

The ECM, including the engineered, cover has a design life of 550 years and is likely to provide a significant degree of protection from water ingress for centuries after the assumed end of Institutional Control, in 2400. Nevertheless, a conservative scenario where the cover system fails at the end of the Institutional Control period, approximately 300 years after the closure of the facility (i.e. at year 2400), was considered. This scenario assumes that at this point the engineered cover of the ECM begins to erode and is no longer maintained. This ingress may lead to partial rehydration of the waste. Further into the future, potentially after thousands of years, the base liner is assumed to develop a leak, allowing a pathway for leachate to reach groundwater. As a result, the level of moisture within the ECM will reduce over time and, ultimately, a steady state will be achieved. Further details on NSDF Project phases are provided below.

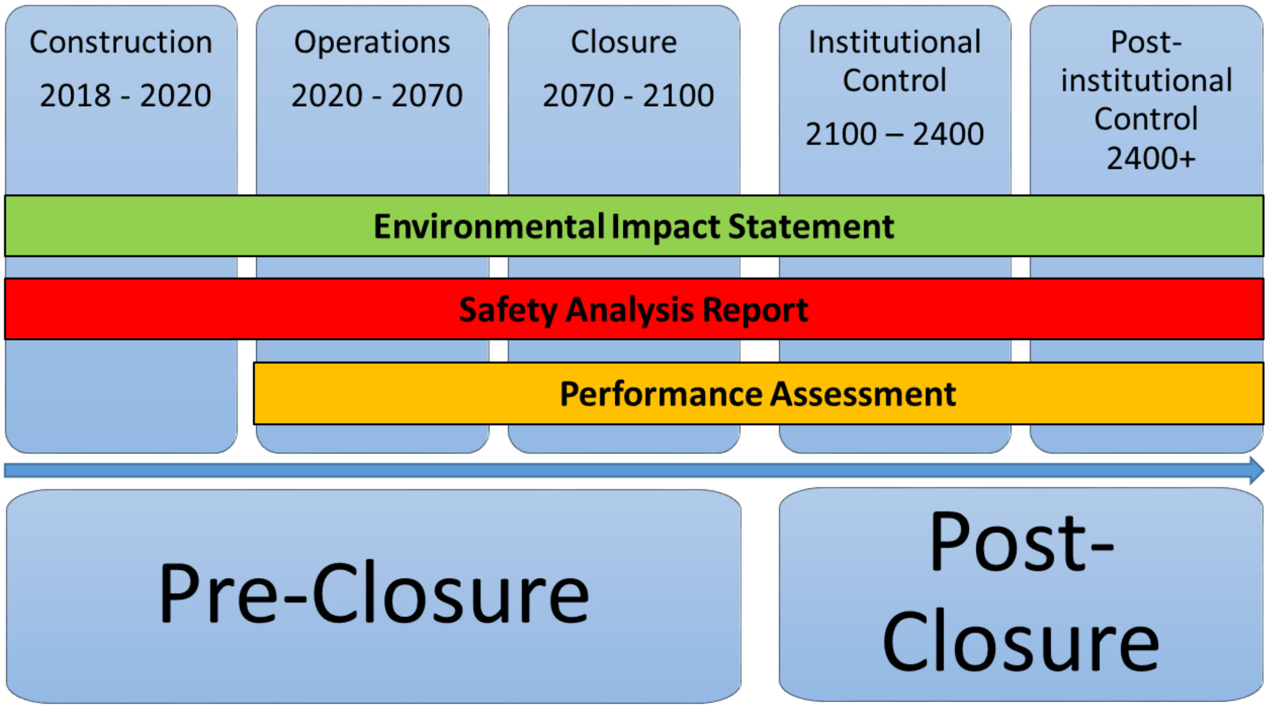

Figure 1-4 Project Timeline

1.7.1 Construction Phase (including site preparation)

The NSDF is planned to be constructed over a two-year period from 2018 to 2020. This phase begins when site clearing activities are initiated, continues through construction and ends when the inactive commissioning of the facility is completed. The NSDF will be built on a clean site and no radioactive materials will be handled at the NSDF during this phase.

1.7.2 Operating Period

The operating period begins at the start of active commissioning. The CNL Radiation Protection (RP) Program will be in place and will limit the radiation exposure to workers that may occur during operations. Monitoring, surveillance and testing programmes will continue to inform management decisions.

Only one cell of the ECM will be open and in active operation (receiving waste) at a time. Precipitation that makes contact with the waste placed in the open cell will be collected. The resulting leachate and contact water will then be treated at the WWTP to meet compliance discharge criteria prior to its release (shown as “Active Leachate Treatment” in Figure 1-5 below). The treated effluent will be discharged to the Perch Lake basin and eventually enter the Ottawa River. The PA studies the effects of the treated effluent on the public and the environment.

When a cell is filled to capacity, it is closed and capped with an interim cover. This reduces the amount of water that comes into contact with the emplaced waste.

Final capping will be constructed in phases, after several cells are filled. As such, while there is always one open cell, there will be a variable number of interim covered cells. This is accounted for in the leachate generation estimates, as discussed in further detail in [1-10].

The operating period ends when the entire ECM is capped and closed, the facility is no longer accepting waste and the leachate is no longer generated. The anticipated operating period of the NSDF is 50 years, i.e. 2020 to 2070.

1.7.3 Closure, Decommissioning and Monitoring Activities

The closure period begins when all of the engineered containment and isolation features have been put into place. Decommissioning activities begin with the operational buildings and supporting services. This phase is anticipated to commence in 2070.

The decommissioning and closure of the WWTP, waste receipt, decontamination facilities, and administrative buildings is dependent on leachate generation rates. The capped mound is designed to divert precipitation, and it is expected that once the ECM is closed and fully capped, leachate generation in the mound will be significantly reduced and quickly become negligible. Therefore, it is anticipated that the WWTP will cease operations shortly (experience demonstrates between 4-8 years) after the ECM is capped. By the end of this period, the waste will have dried out, and the generation of leachate will be minimal, allowing for the WWTP to be decommissioned. The closure period extends up until about 2100.

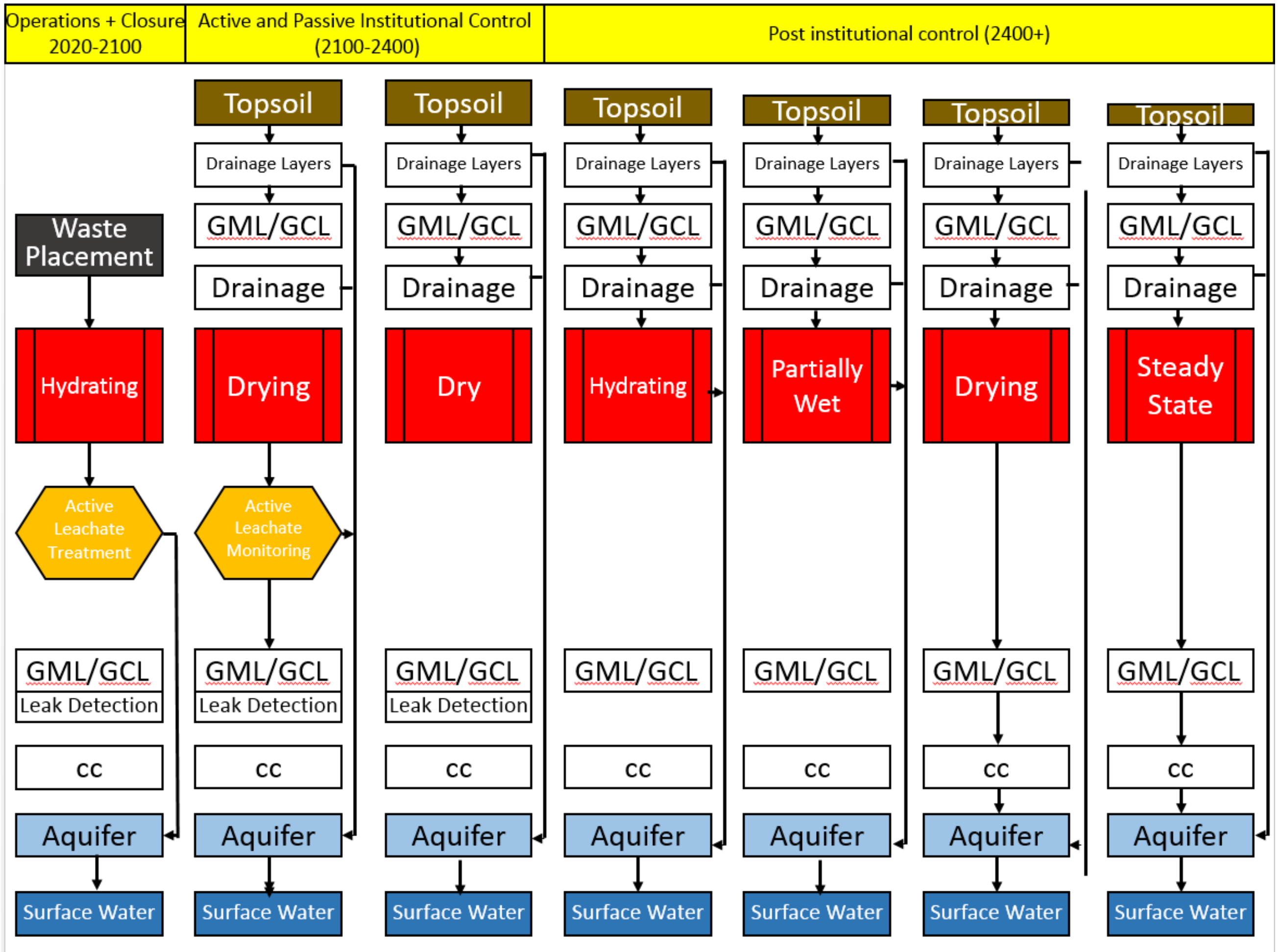

Figure 1-5 Long-term Performance of the Engineered Containment Mound

GML – Geomembrane; GCL - Geosynthetic Clay Liner; CC - Compacted Clay

Active Leachate Treatment – refers to treatment in the WWTP

1.7.4 Post-Closure Period, Including Active Monitoring and Passive Institutional Control

This period begins when all closure and decommissioning activities for the NSDF have taken place. This period is assumed to begin around 2100.

After the closure of the NSDF, safety will be provided through the passive engineered barriers. The NSDF and surrounding area will continue to be actively monitored to ensure that the barriers are functioning as designed, and that radiation dose rates to the public and environment are ALARA. If required, based on the monitoring activities, maintenance will be provided e.g. for the cover and/or surface water run-off systems, to ensure the waste remains dry.

During active Institutional Control, the NSDF will be actively monitored for the duration of the licence. Approval will be required from the CNSC to release the site from regulatory control. The conditions required to grant this approval may change during the post-closure period, however, it is understood that the site will not be released from regulatory control until it can be demonstrated that the hazard posed by the facility is acceptably low.

Passive Institutional Control refers to the activities taking place following the release from regulatory control. The role of Institutional Controls is to ([1-4], [1-11]):

- Ensure long-term safety.
- Reduce the probability of intrusion.
- Reduce the consequence of intrusion.
- Expedite the intervention and remediation.
- Provide societal confidence in the safety of a waste facility.

1.8 Adjacent Waste Management Areas

This section introduces relevant information about the WMAs adjacent to the NSDF on the CRL site, located in the Perch Lake Basin.

1.8.1 Perch Lake Basin

The WMAs that are located in the Perch Lake Basin (see Section 3) are legacy waste storage sites. No new waste streams are being placed into these facilities. In some cases, legacy storage practices resulted in environmental releases, which are monitored and controlled by CNL to ensure that potential environmental risks are acceptable [1-12].

Several existing facilities, including WMA A and B and the Liquid Dispersal Area (LDA) (which includes Reactor Pit 1, Reactor Pit 2, Laundry Pit and the Chemical Pit), are also located in the Perch Lake Basin. For perspective, Figure 1-6 shows the basins, and the facilities that release into them, for the overall Chalk River Laboratories site.

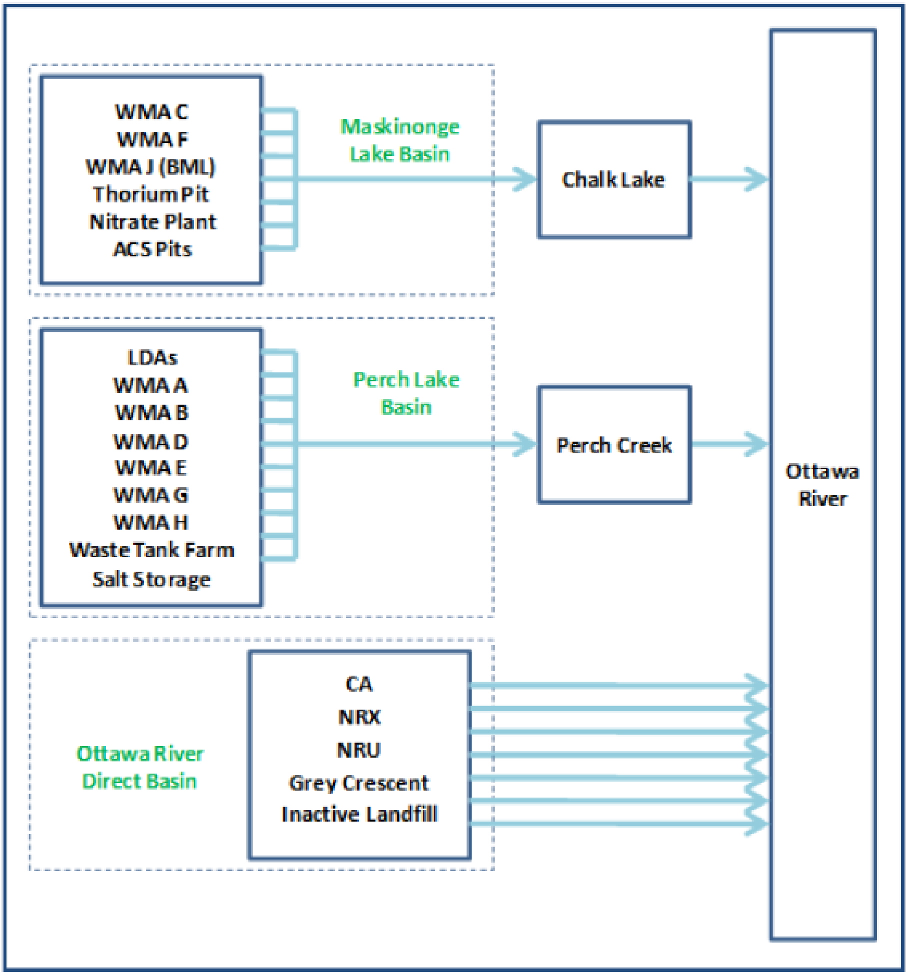

Figure 1-6 Chalk River Laboratories Site Model Overview [1-12]

1.8.2 Location of Waste Management Areas

The WMAs provide various facilities for storing radioactive wastes ranging in activity from very low levels up to that of irradiated nuclear fuel. All waste areas are licensed under a single facility authorization, which includes nine WMAs plus dispersal areas. Waste Management Areas include operating facilities currently accepting wastes and non-operating facilities that are no longer accepting waste.

A description of the WMAs located within the Perch Lake Basin is included below to give context to the waste facilities adjacent to the proposed NSDF site. Some of the waste streams currently stored within WMAs will be recovered and disposed in the NSDF.

The location of the WMAs is shown in Figure 1-7. Both WMA A and the LDA are located in close proximity to the NSDF site. The nearest off-site residents are located at the western boundary of the CRL site in Chalk River, approximately 5 km from the facility. Calculations are done at 3 km to be conservative.

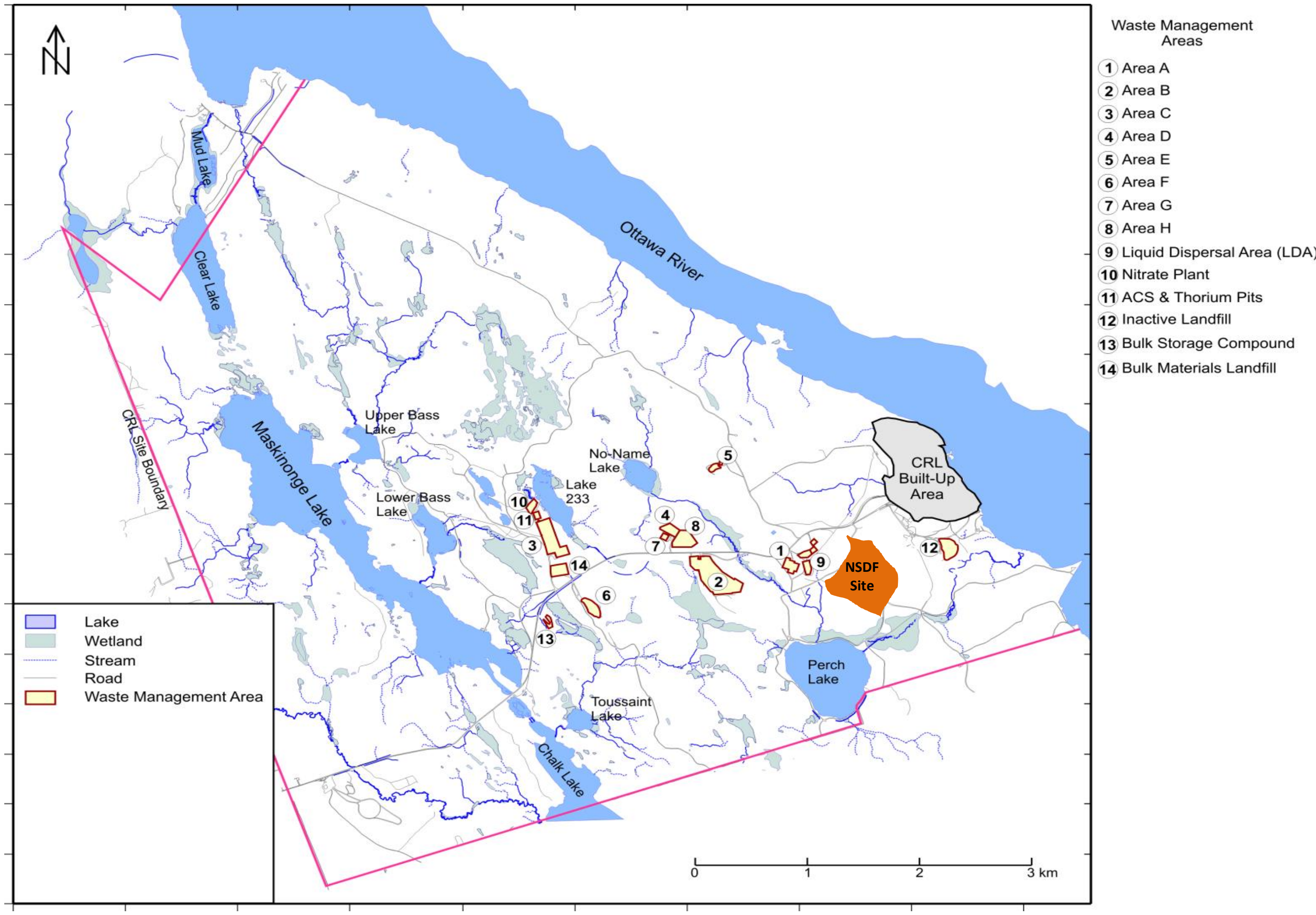

Figure 1-7 Plan View of the Chalk River Laboratories Site Showing Location of Waste Management Areas

1.8.3 Liquid Dispersal Area

The LDA contains Reactor Waste Dispersal Pits #1 and #2, Chemical Dispersal Pit and Laundry Pit, which are all legacy facilities, no longer used for waste placement. The LDA is located to the west of the NSDF site and drains towards East Swamp Stream, which in turn discharges into Perch Lake. Altogether there is one natural and three man-made pits that were designed and sited as seepage pits to disperse low-level radioactive liquids into the soil/ground system so that radionuclides are absorbed onto the soil thereby, slowing their migration rate to permit decay of radioactivity while water still passes through the system.

1.8.4 Waste Management Area A

Waste Management Area A is a 1.2 hectare (ha) area located within the Perch Lake Basin, immediately to the west of the LDA, south of the Plant Road approximately 1.2 km west of the built-up area. The facility was in operation in the 1940s and 1950s. The solid wastes were placed in unlined trenches and in a variety of small engineered structures. Liquid wastes were discharged to infiltration pits. The facility is closed and no longer accepts wastes. There is a contaminant groundwater plume emanating from WMA A, primarily containing Sr-90 that flows towards South Swamp, which is a small wetland located about 70 m south of WMA A. A permeable reactive barrier has been installed and is successfully removing Sr-90 from groundwater upgradient of South Swamp.

1.8.5 Waste Management Area B

Waste Management Area B is a 14 ha area located within the Perch Lake Basin, south of Plant Road, approximately 0.6 km west of WMA A and approximately 1.8 km west of the CRL built-up area. Waste Management Area B is currently operational and includes engineered radioactive and hazardous waste storage and handling facilities. The land to the west consists of the West Swamp, which receives a Sr-90 groundwater plume emanating from WMA B that is treated by a pump and treat system. The swamp then drains down a shallow valley, eventually entering Perch Lake.

1.8.6 Waste Management Area D

Waste Management Area D is a 1.3 ha site located within the Perch Lake Basin approximately 2 km west of the CRL built-up area. Waste Management Area D is an operational facility with above ground storage of contaminated equipment and mixed wastes.

1.8.7 Waste Management Areas H and G

Waste Management Area H is an operational facility, located in the Perch Lake Basin approximately 2 km west of the CRL built-up area, adjacent to WMA D and WMA G. Waste Management Area H is situated on a 3.4 ha triangular shaped area, bounded on the south by Plant Road and by two small stream valleys on the north and east. Runoff water from the eastern portion of the site drains into the swampy area of Main Stream, which drains to Perch Lake via Perch Lake Inlet 2. Waste Management Area H contains engineered above ground storage buildings with containerized low-level waste.

Waste Management Area G is a non-operational facility adjacent to WMA H that was established in 1988 for the above-ground storage of the entire inventory of irradiated fuel from the NPD prototype CANDU power reactor at Rolphton in concrete canisters. There is also a small amount of CANDU fuel from Bruce, Pickering and Douglas Point. There are three containment barriers that independently prevent releases to the environment.

1.9 Software and Quality Assurance Measures

1.9.1 Program and Management Quality Assurance Plan

This project is being designed to meet ISO 9001 requirements with software for analysis needing to satisfy Canadian Standard Association (CSA) N286.7. Canadian Nuclear Laboratories' Quality Assurance (QA) documentation [1-13] describes the organization, responsibilities, processes, and controls used for computer analysis and operations. These procedural documents satisfy various program and licensing requirements such as, CSA N286-12 [1-14] and CAN/CSA-ISO 9001 (current version) [1-15], Quality Management System – Requirements and is supplementary to the CNL management and QA procedures. The QA program is applicable to project management, engineering, technical analysis, operations, and other work carried out in support of the management of radioactive waste.

The analysis of the selected scenarios uses the conceptual site model and mathematical models implemented in compartmental modelling software. Only computer programs that are CNL Code Management Panel approved for use, and meet the requirements for Analytical, Scientific and Design Computer Programs, will be used in support of the safety analysis and technical assessments for activities applicable to nuclear facilities [1-13].

Throughout the preparation of this PA, the analysis has used methods and approaches used for similar facilities in Canada and internationally (e.g. [1-16], [1-17], [1-18], and [1-19]). The analysis was subjected to an internal review and verification in accordance with CNL's QA program as well as to an independent third party review.

1.9.2 IMPACT

The IMPACT code was used for the calculation of potential doses to members of the public, resulting from radionuclide releases to water and atmosphere. IMPACT is a customizable tool that allows the user to assess the transport and fate of contaminants through a user-specified environment. IMPACT also enables the quantification of human exposure to those environmental contaminants and the calculation of Derived Release Limits (DRLs) for nuclear facilities (power generating stations, research reactors, waste management facilities). The code covers all of the potential exposure and release scenarios, including atmospheric and aquatic pathways that are in the CSA N288.1-14 [1-20].

IMPACT Version 5.5.1 was released in 2016 and is the latest version of the code available at this time. The code was developed by EcoMetrix Inc. under contract to the CANDU Owners Group. The development of IMPACT 5.5.1 has been guided by, and subject to, an overall Tool Qualification Program, which follows the CSA N286.7 [1-21]. Code verification and validation were documented in the Tool Qualification Report [1-22]. A user manual and theory manual are also available for this version [1-23] and [1-24].

Using IMPACT, DRLs have been calculated for the CRL process outfall to the Ottawa River [1-25] in accordance with the CSA N288.1 [1-20]. The pathway analysis model, receptor groups, and dietary habits used as the basis for the existing Chalk River DRL model, were updated to evaluate effective doses to potential exposure groups and to incorporate the results of a recent lifestyle survey conducted by CNL [1-26]. Modifications account for future conditions corresponding to various evolution scenarios. The modifications also addressed biosphere transfers of additional radionuclides, which needed to be considered in the context of disposal.

The CSA N288.1, which is the theoretical basis for the IMPACT code, specifies that it is applicable to the analysis of releases from many nuclear facilities, including waste management facilities. However, it is not suitable for extensive modelling of groundwater pathways [1-20].

IMPACT is designed to analyze chronic releases occurring over long periods of time and is not suitable for representing short-term exposures associated with certain disruptive scenarios. For this reason, the processes that could potentially result in radionuclides leaching from the disposal facility and contaminant transport in the groundwater, as well as post-closure assessment human intrusion calculations, were evaluated using RESRAD-OFFSITE [1-27].

1.9.3 RESRAD

RESRAD-OFFSITE (Version 3.1) was selected to calculate the radionuclide concentrations in the leachate, the contaminant transport in the groundwater, the radon flux at the surface of the landfill and the doses from inadvertent intrusion (and related exposures) as part of the post-closure assessment.

RESRAD-OFFSITE is a computer program that has been approved for use at CNL and is used extensively for PAs thoughout the United States and other parts of the world. RESRAD-OFFSITE [1-27] is being used to calculate the radionuclide release mechanism and contaminant transport in the geosphere.

The release mechanism to be modelled in each scenario (unless otherwise specified), is the RESRAD-OFFSITE Version 2 release methodology, which is a first-order exponential leaching model. The Version 2 release mechanism is a first-order release without transport option, where the user may specify the leach rate, or the code will estimate the radionuclide leach rate from the specified distribution coefficient [1-27].

As described in the User's Manual [1-27], RESRAD underwent extensive review, benchmarking, verification, and validation. Verification of the mathematical models was documented through hand calculations and spreadsheets. The code has been benchmarked against several models that can be used to conduct similar tasks, including GENII-S, DECOM and PATHRAD-EPA codes.

Validation tasks to test the mathematical model against accurately measured, independent sets of field or laboratory observations over the range of conditions for model applications were conducted for various sub-models: leaching model and against real world data collected after the Chernobyl accident.

A comparison of half lives embedded in RESRAD OFFSITE 3.2, to those in ICRP 38 (the source of half lives used for RESRAD) shows that a few radionuclides, notably Cs-135, I-129, U-233, and Zr-93, have half lives that are larger than those presented in ICRP 38. The implication to this PA is that the dose estimates for these radionuclides is conservative.

The groundwater model, supporting the RESRAD contaminant transport analysis, was developed using MODFLOW-2005, as documented in a separate groundwater flow modelling study for the NSDF site [1-28]. MODFLOW-2005 [1-29] is a multi-purpose three-dimensional groundwater flow code developed by the United States Geological Survey. MODFLOW is modular in nature and uses the finite difference formulation of the groundwater flow equation in its solution.

1.10 Definitions

Accident – any unintended event, including operating errors, equipment failures or other mishaps, the consequences or potential consequences of which are not negligible from the point of view of protection or safety.

ALARA – the principle of keeping radiation doses As Low As Reasonably Achievable, social and economic factors taken into account.

Anticipated Operational Occurrences – an operational process deviating from normal operation that is expected to occur once or several times during the operating lifetime of the facility but which, in view of the appropriate design provisions, neither causes any significant damage to items important to safety nor leads to accident conditions.

Caisson - a large shielded watertight container.

Contact Water – precipitation or surface water that contacts waste in the temporary storage area or as it is being emplaced into the ECM. This water does not contact the waste for as long as leachate does, but is still potentially contaminated.

Critical Group – a fairly homogeneous group of people whose location, age, habits, diet, etc. causes them for a given radionuclide, release location and release characteristics, to receive effective dose or equivalent dose (as applicable) higher than the average received by other groups in the exposed population.

Disposal – emplacement of waste in an appropriate facility without the intention of retrieval.

Disruptive Event – an occurrence that is outside the normal operating parameters, usually relating to an event with detrimental effects.

Hazard – a potentially damaging physical event, phenomenon or human activity that may cause the loss of life or injury, property damage, social and economic disruption, or environmental degradation. Source: An Emergency Management Framework for Canada.

Event – any unintended occurrence, including operating error, equipment failure or other mishap, or deliberate actions on part of others, the consequences or potential consequences of which are not negligible from the point of view of protection or safety.

Note: The definitions of the terms ‘event’ and ‘accident’ as used in the CRL Handbook, are identical in essence. The difference derives from the fact that ‘event’ reporting is concerned with the question of whether an ‘event’ that could develop into an ‘accident’ actually does so. The term ‘accident’ is used to describe the end result, while the term ‘event’ is used to describe the earlier stages.

Features, Events, and Processes (FEPs) – a systematic evaluation of factors (i.e. Features, Events and Processes) that may be important to the post-closure safety assessment.

Human Intrusion – see Inadvertent Intrusion.

Inadvertent Intrusion – for the purposes of this document, Inadvertent Intrusion refers to the act of digging or excavating into the ECM or settling on top of the mound without the knowledge of the potential hazards and health risks associated with the activity.

Indicator Species – a species which represents a selection of similar species when performing an EA. For example, studies performed for the Blanding's Turtle may be applied to other turtle species, as long as they have similar habitats, diets, lifecycles, etc.

Intermediate-Level Waste – intermediate-level waste (ILW) typically exhibits levels of penetrating radiation sufficient to require shielding during handling and interim storage. A precise boundary between LLW and intermediate-level waste (ILW) cannot be provided, as limits on the acceptable level of activity concentration will differ between individual radionuclides or groups of radionuclides.

Leachate – precipitation that infiltrates the waste once it has been emplaced in cells, and is assumed to be slightly contaminated with radionuclides and other hazardous constituents (or constituents of potential concern).

Low-Level Waste – low-level waste (LLW) contains material with radionuclide content above established clearance levels and exemption quantities, but generally has limited amounts of long-lived activity.

Near Surface Facility – a facility for radioactive waste storage located at or within a few tens of metres of the Earth's surface.

Normal Evolution – the normal expected progression for a facility to follow. This usually refers to the effects of the environment on the project over the course of hundreds or thousands of years. Normal evolution assumes that no accident conditions have taken place.

Nuclear Energy Worker – a Nuclear Energy Worker (NEW) is defined by the. Nuclear Safety and Control Act as a person who is required, in the course of the person's business, or occupation in connection with a nuclear substance or nuclear facility to perform duties and such.

Nuclear Safety – nuclear safety is defined by the International Atomic Energy Agency (IAEA) as the achievement of proper operating conditions, prevention of accidents or mitigation of proper operating conditions, resulting in the protection of workers, the public and the environment from undue radiation hazards.

Operating Facility – an operating facility is a facility that is approved to receive waste for storage.

Operational Limits and Conditions – operational limits and conditions are a set of rules setting forth parameter limits or conditions that ensures the functional capability and the performance level of equipment for safe operation of the nuclear facility. Operational limits and conditions are referred to as limiting conditions for safe operation in the licensee's facility authorization documents.

Over pack – an over pack is a container that provides protection, secondary containment, convenience in handling a waste package, or consolidation of one or more waste packages.

Post-closure – the phase following the closure of the facility.

Potential Critical Group – hypothetical members of the public who have been identified as the most sensitive to CRL operations, and who would be the most affected by effluent releases, based on proximity to CRL and other individual factors, such as diet.

Potential Exposure Group – Specific to post-closure safety assessment – a hypothetical group was used to asses the doses to future humans.

Pre-closure – the phase before closing the facility, i.e. the construction and operations phases.

Processing – activities involved with waste handling at the WMA facility prior to storing in a facility, which may include incoming inspection, compaction and loading into storage containers.

Run-off – water that has come into contact with clean materials on the site. Run-off is collected in the storm water management points.

Storage – activities associated with putting waste packages into a storage facility and maintaining the safe storage state afterward.

Valued Component – a valued component (VC) is an element of the environment that has scientific, economic, social, or cultural significance. Those VCs that may be affected by a project's activities are included in the EA.

Waste Management Area – the WMA is a licenced facility on CRL property that stores radioactive waste. The WMA is comprised of several sub areas, denoted with letters and other specific names (WMA A, WMA B, the Fuel Packaging and Storage facility, etc.).

1.11 Acronyms

AECL	Atomic Energy of Canada Limited
AL	Action Levels
ALARA	As Low as Reasonably Achievable
CM	Contamination Monitor
CNL	Canadian Nuclear Laboratories
CNSC	Canadian Nuclear Safety Commission
CRL	Chalk River Laboratories
CSA	Canadian Standard Association
CSD	Criticality Safety Document
CWAC	Conceptual Waste Acceptance Criteria
DBA	Design Basis Accident

DOE	Department of Energy
DRL	Derived Release Limit
EA	Environmental Assessment
ECM	Engineered Containment Mound
EIS	Environmental Impact Statement
ERA	Environmental Risk Assessment
FEP	Features, Events and Processes
FM	Fissionable Material
ha	Hectare
HDPE	High-Density Polyethylene
HIDP	Human Intrusion in the context of Disposal of Radioactive Waste
HSSE	Health, Safety, Security, and Environment
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ILW	Intermediate-Level Waste
LDA	Liquid Dispersal Area
IX	Ion Exchange
LLW	Low level Waste
Kilometer	Km
mASL	Meters above sea level
NBCC	National Building Code of Canada
NEW	Nuclear Energy Worker
NSCA	Nuclear Safety and Control Act
NSDF	Near Surface Disposal Facility

OSH	Occupational Safety & Health
PCG	Potential Critical Groups
PGA	Peak Ground Acceleration
PMP	Probable Maximum Precipitation
PSHA	Probabilistic Seismic Hazard Analysis
QA	Quality Assurance
RO	Reverse Osmosis
RP	Radiation Protection
RS	Radiation Surveyor
SAR	Safety Analysis Report
SFL	Screening Frequency Level
USL	Upper Subcritical Limits
VC	Value Components
WAC	Waste Acceptance Criteria
WMA	Waste Management Area
WQSZ	Western Quebec Seismic Zone

1.12 References

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[1-24] EcoMetrix, *Theory Manual for Impact 5.5.1,* 2016 January.

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2. DEFINITION OF SAFETY OBJECTIVE AND SAFETY CRITERIA

According to the IAEA Safety Requirements [2-1], the safety objective for a radioactive waste disposal facility is to:

"…site, design, construct, operate and close a disposal facility so that protection after its closure is optimized, social and economic factors being taken into account. A reasonable assurance also has to be provided that doses and risks to members of the public in the long-term will not exceed the dose limit for members of the public and other risk constraints".

This statement is consistent with the CNSC guidance [2-2], which states that the objective is to:

"*… evaluate feasibility of assuring that dose and risk objectives can be met by assessing the potential long-term impact that radioactive waste disposal may have on the environment and on the health and safety of the people*".

Therefore, the PA addresses two principle objectives:

1. Protect people from harmful effects of ionizing radiation.
2. Protect environment from harmful effects of ionizing radiation.

The SAR will address protection of people and the environment from the harmful effects of hazardous substances, and, will outline design optimization.

2.1 Members of the Public

In order to demonstrate that the safety objective is met, IAEA [2-1], CNSC [2-2] and CNL's Licence Conditions Handbook [2-3], provide specific dose limits and other constraints. Criteria applicable to radiological exposure of members of the general public include:

- Effective dose limit of 1 mSv per year [2-2].
- Canadian Nuclear Laboratories Licensing limit of 0.3 mSv over any period of 12 consecutive months [2-3].

Use of the 0.3 mSv/y limit in the post-closure assessment of public doses is in keeping with Regulatory Guide G-320 [2-2] to ensure that public doses remain below 1 mSv/y in the future, accounting for the possibility of exposure to multiple sources. For the post-closure assessments this will be referred to as a dose constraint. For the post-closure assessments this will be referred to as a dose constraint.

The PA document will clearly specify how compliance with the Safety Objective can be demonstrated.

2.2 Workers

The safety objectives that follow from CNL's policies and compliance programs ensure that:

1. Radiation exposures to facility staff, on-site personnel and the off-site public resulting from the normal facility operation, Anticipated Operational Occurrences and credible accidents are:

- Below the regulatory limit [2-2] of 50 mSv/y to a maximum of 100 mSv in 5 years.
- As Low as Reasonably Achievable (ALARA).
- As per internal Radiation Protection Requirements [2-4].

2. Radioactive releases and radiation exposures to the facility staff, on-site personnel and the most exposed group of the off-site public resulting from abnormal events will be addressed with the defence-in-depth philosophy. Dose will be:
   - First prevented
   - Mitigated
   - Accommodated through design, operating procedures, training, and administrative controls.
3. Releases of radiological substances to the environment will be first prevented, then mitigated, and then accommodated as such that exposures are minimized and are ALARA.

In addition to the safety criteria outlined above, CNL also has an internal occupational dose target of 1 mSv/y. Though not a safety criterion, this target value is useful for dose optimization in keeping with the ALARA principle. Similarly, an administrative level of 5% of the Annual Limit on Intake also exists for optimization purposes.

2.3 Accident dose criteria

The following table describes the dose criteria for accident scenarios, as per CNL's Conduct of Safety Engineering [2-5].

Table 2-1 Dose Acceptance Criteria for Accidents

Frequency Range (event/year)	Qualitative Event Occurrence Frequency[1]	Dose Range (mSv)	
		On-site Personnel	Offsite Individual of the Public
$<10^{-6}$	**Beyond Extremely Rare**; Beyond Design Basis Accident	-	-
10^{-6} to 10^{-4}	**Extremely Rare**; events are not expected to occur during the lifetime of the facility.	5 to 100	50 to 100
10^{-4} to 3×10^{-2}	**Rare**; events have slight chance of occurring during the lifetime of the facility.	0.5 to 5	5 to 50
3×10^{-2} to 3×10^{-1}	**Occasional**; events may occur a few times during the lifetime of the facility.	0.1 to 0.5	1 to 5
$>3 \times 10^{-1}$	**Frequent**; events that are expected to occur several times during the lifetime of the facility.	<0.1 mSv/event	<1 mSv/event

[1] Frequent; several times a year to once in several years, Occasional; may occur several times during the facility lifetime, Rare; accidents that are not anticipated to occur during the lifetime of the facility, Extremely Rare; accidents that will probably not occur during the life cycle of the facility.

2.4 Inadvertent Intruders

The IAEA [2-1] defines "Human Intrusion" as:

> *Human actions that affect the integrity of a disposal facility and which could potentially give rise to radiological consequences. Only those human actions that result in direct disturbance of the disposal facility (i.e. the waste itself, the contaminated near field or the engineered barrier materials) are considered.*

The CNSC postulates that Human Intrusion involving direct disturbance of disposed wastes needs to be considered, but only for inadvertent intrusion scenarios [2-2].

Neither the legal dose limit of 1 mSv/y nor the dose constraint of 0.3 mSv/y to members of the public apply to doses resulting from inadvertent human intrusion. For human intrusion IAEA postulates that [2-1]:

- If intrusion is expected to lead to an annual dose of less than 1 mSv, then efforts to reduce the probability of intrusion or to limit its consequences are not warranted.
- If intrusion is expected to lead to annual doses in the range of 1 – 20 mSv, then efforts to optimize design are warranted to reduce the probability of intrusion and limit the consequences.
- If intrusion is expected to lead to an annual dose in excess of 20 mSv, then alternative disposal options should be considered.

2.5 Non-Human Biota

The NSCA and regulations specify protection of both the environment and persons. Therefore, in accordance with Regulatory Guide G-320 [2-2], long-term assessments should address the impact on non-human biota.

The primary concern in the protection of nonhuman biota from radiation exposure is the total radiation dose to the organisms, resulting in deterministic effects. The following dose benchmark values, as recommended in Canadian Standards Association (CSA) N288.6-12 [2-6] will be used in this work for the purpose of the assessment:

- 100 µGy/h for terrestrial biota.
- 400 µGy/h for aquatic biota.

These benchmark values are designed to protect populations of non-human biota. They were derived for screening purposes and are very conservative. If the calculated dose is less than the criteria, then the radiological risk is considered acceptable and no Detailed Quantitative Risk Assessment is warranted. Otherwise, a Detailed Quantitative Risk Assessment should be conducted along with the identification of mitigation measures.

2.6 References

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[2-5] *Conduct of Safety Engineering*, 145-508770-PRO-001, Revision 5, 2015 April.

[2-6] Canadian Standards Association, Envir*onmental Risk Assessments at Class 1 Nuclear Facilities and Uranium Mines and Mills*, N288.6-12, 2012 December.

3. SITE CHARACTERISTICS

The CRL property is located in Renfrew County, Ontario on the shore of the Ottawa River. The site contains several licence-listed nuclear facilities, including the National Research Universal reactor, WMAs and many other nuclear and non-nuclear facilities and laboratories. Two hydro lines cross the CRL property and provide electricity for CRL operations. The property has a total area of 38.7 km^2, is located approximately 185 kilometres (km) northwest of Ottawa, and is within the boundaries of the Corporation of the Town of Deep River. The Federal Department of National Defence Garrison Petawawa borders the CRL property to the southeast, and the Village of Chalk River in the Municipality of Laurentian Hills is to the southwest. The Ottawa River forms the northeastern boundary of the property. Populations of the surrounding areas are discussed in Section 3.1. The NSDF Project is located entirely within the CRL property (Figure 3-1) [3-1].

Chalk River Laboratories is designated into three radiological areas [3-2]. The Plant Road and parking lots are designated *Uncontrolled Areas*, the built-up area and WMAs are designated *Controlled Areas* and the remaining areas (the “bush” areas) are designated *Supervised Areas* [3-2]. However, access is controlled to all locations within the CRL property.

The Ottawa River is the dominant drainage feature in the area. The CRL site contains several small drainage basins that either drain directly to the Ottawa River or to smaller lakes and streams, which in turn drain to the Ottawa River. The CRL property is located in the Allumette Lake and Lac Coulonge reach of the Ottawa River, which extends approximately 90 km between La Passe and the Des Joachims Dam. The distance from the centre of the NSDF Project site to the closest point on the Ottawa River is approximately 1 km. Perch Lake is located southwest of the NSDF Project site (Figure 3-1).

Aside from the operations and activities undertaken by CNL, other land uses of the CRL property are prohibited due to restricted public access. No hunting or fishing is permitted on the CRL property and the property is not used for traditional purposes by indigenous and metis communities [3-3]. Land use in the region consists primarily of forestry, recreation and tourism, with limited agriculture, trapping and mining [3-3]. The nearest area of considerable agriculture and dairy farming is 15 km southeast on the Quebec side of the Ottawa River and 35 km southeast on the Ontario side. The Ottawa River is an important recreational resource for swimming, sport fishing and boating; there is little commercial fishing opportunity. There are several sand beaches along both sides of the river that provide popular recreational sites. In addition, two provincial parks, Algonquin and Driftwood, are in close proximity to CRL, which offer opportunities for canoeing, hiking, fishing, and hunting. Winter recreational activities in the region include cross-country skiing, snowmobiling and ice-fishing.

This section provides information on hydrology, geology, hydrogeology, climate, relevant populations, and ecology. Additional, recent, information on these topics is available in Section 3 of the EIS [3-4].

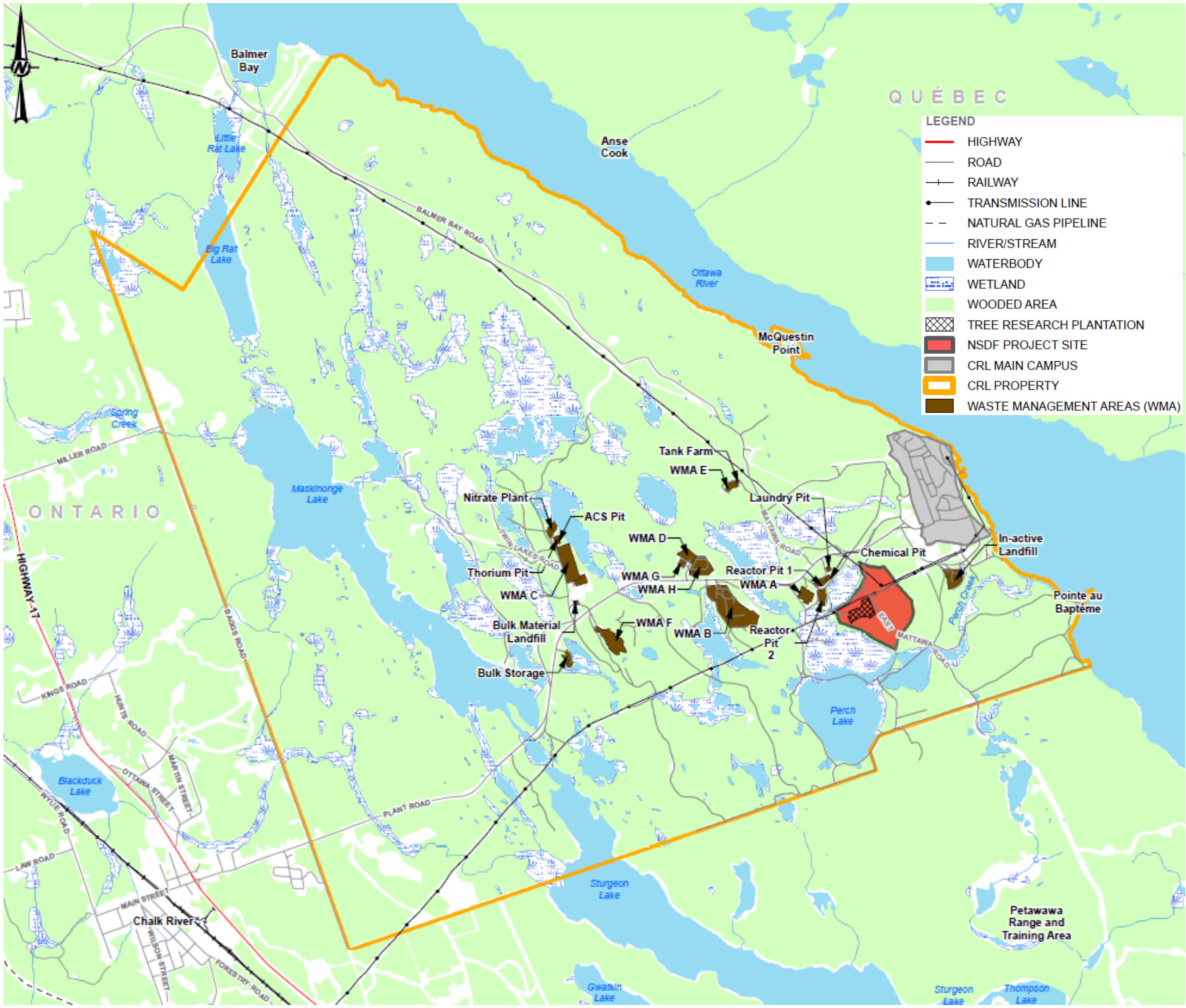

Figure 3-1 Location of Proposed NSDF site at CRL (Golder, 2017)

3.1 Population Relevant to the Analysis

The number of people living in the area has been relatively constant. According to the 2011 census data, the majority of the population surrounding CRL live in:

- Ontario in Renfrew County, with 101 326 people.
- Quebec in sparsely populated Pontiac County, with 14 358 people.

The majority of local residents live close to and around the town of Deep River and the Village of Chalk River. The Village of Chalk River has approximately 1 200 residents and is 5.5 km by the road to the west of CRL. Although the CRL site is within the boundary of the Town of Deep River, the closest of the town's residents reside at Balmer Bay, 7.0 km from the centre of the proposed NSDF footprint. Surrounding these two population centres are Rolphton, Buchanan, Wylie, and McKay, which, with Chalk River, form the municipality of Laurentian Hills. The total population of Laurentian Hills is nearly 2 800 people. The Town of Petawawa, the amalgamated surrounding townships and the military base, are 20 km downstream from CRL and have a total combined population of approximately 16 000 residents. Another large population centre is Pembroke and area, with about 14 400 residents, 35 km downstream from CRL. North Bay and Ottawa are more than 150 km (straight line) west-northwest and up and 150 km east-southeast, respectively.

The portion of Pontiac County in the Province of Quebec, north east of the river and opposite the site, is normally uninhabited, except during the summer months when a few cottage dwellers may be present. The closest permanent residents are 8.2 km downriver, in the Downey Bay area. The closest centres of population on the Quebec side are Fort William and Sheenboro, about 15 km down river, with combined populations of about 160 residents.

The population density within 20 km and 40 km radii are approximately 18.30 and approximately 7.6 person/km^2 respectively (the population of the region reflects permanent residents only).

For perspective, Figure 3-2 shows the locations of public receptor locations as noted in the CRL DRL [3-5].

It should be noted that there are other large population centers, further downstream of the facility. However, these distant population centers will not be affected if the closer population centers are not affected. Therefore, focusing on nearby population centers is conservative.

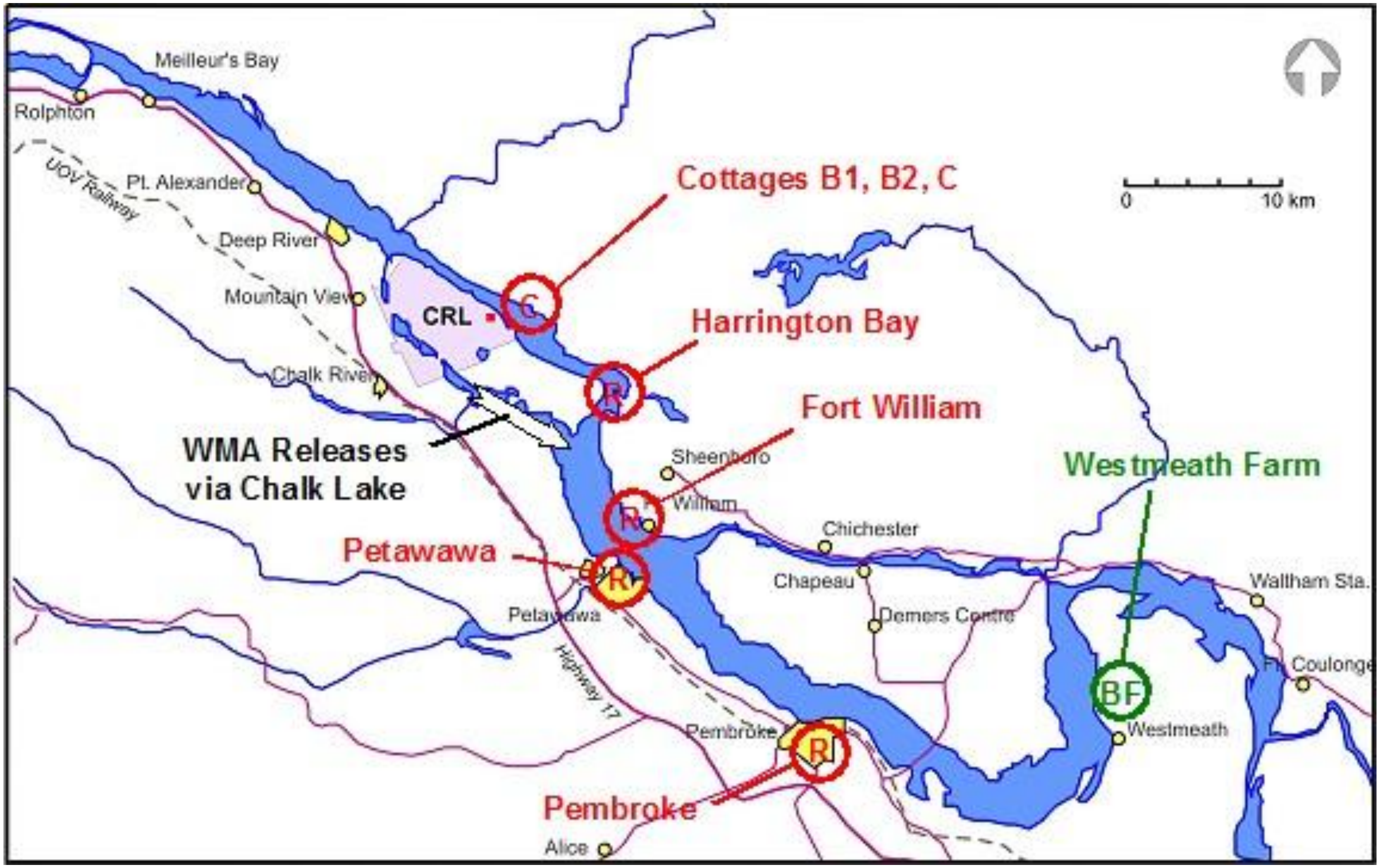

Figure 3-2 Public Receptor Locations from the CRL DRL [3-5]

3.1.1 Potential Critical Groups

The CRL Site Characteristics report [3-1], describes the critical group as an identifiable, relatively homogeneous group of members of the public who, as a result of their location, age, diet, and habits, are representative of those people expected to receive the highest radiation doses as a result of emissions of a given radionuclide from a given source. The Potential Critical Groups (PCGs) which have been identified for the CRL site survey are shown in Table 3-1, along with their distance to the NSDF. They were selected by evaluating doses to members of 22 PCGs that were considered based on lifestyle and proximity to the CRL site. The critical groups listed in Table 3-1 are those that are likely to receive the highest radiation doses as a result of CRL operations. The groups identified for the air effluent pathway are located upstream of the Ottawa River and will not be exposed to waterborne releases. They are, however, more likely to be exposed to higher levels of atmospheric releases due to proximity to the atmospheric release sources and their location along one of the prevailing wind directions. The Liquid Effluent PCG may be exposed to both liquid and atmospheric releases.

Dose calculations are performed for a hypothetical adult, ten year old child and one year old infant using the results of environmental monitoring at and around critical group locations for air effluent and liquid effluent exposure pathways. The characteristics assigned to these individuals are conservative in that the doses calculated are expected to be higher than the maximum dose that might be measured for any real individual.

Table 3-1 Potential Critical Groups for Chalk River Laboratories [3-5]

Air Effluent PCGs		Liquid Effluent PCGs	
Location	Distance to NSDF (km)	Location	Distance to NSDF (km)
Cottager[1]	3	Cottager[1]	3
Mountain View	8	Laurentian Valley	36
Balmer Bay	7	Pembroke	30
Chalk River	5	Petawawa	25
Deep River	12		

Note: 1 – Cottagers are assumed to be present approximately 8% of the year

3.1.2 Food Consumption

One of the pathways to radiation exposure is through ingestion of food. Food that is sourced from within a local boundary surrounding CRL is susceptible to radioactive contaminants. A lifestyle survey was conducted to learn more about the behaviour of the people living in the area with regards to their consumption of local food from sources like farmer's markets, local farms, or grown on their own property. Information regarding identification as Indigenous or Métis, was also requested in order to delineate any difference in food consumption behaviours. Almost 300 members of the public completed the lifestyle survey [3-3].

The results of the survey indicated that those who were identified as Indigenous or Métis did not have statistically different levels of local consumption rates compared with other members of the public. Therefore, when making modelling assumptions for members of the public and Indigenous or Métis, the same coefficients for locally sourced food will be used for all groups.

This methodology is consistent with N288.1-14 [3-6], which specifies that site-specific data for local consumption rates are preferred over the standard values listed.

3.1.3 Potential Exposure Groups During Post-Closure

In order to address uncertainties in the location of population groups that may be impacted by the NSDF in the remote future following the end of Institutional Control, several modelling assumptions have been made. A hypothetical potential exposure group was introduced. This group was assumed to reside on the shores of the Ottawa River, adjacent to the Perch Creek discharge. In this scenario, the dilution is minimized as the significant additional dilution within the Ottawa River is not credited, which results in a bounding estimate of future doses.

3.1.4 Post-Closure Food Consumption

The diet of a hypothetical future exposure group is associated with a large uncertainty. In order to account for this, the post-closure critical group was assumed to have a higher local fraction (i.e. 100%) for the consumption of foods and water sources (see Section 8.8.1). This was a conservative assumption that resulted in conservative dose estimates. A sensitivity analysis was performed to evaluate the significance of a diet with a greater portion of locally sourced food and water (see section 8.8.1).

3.2 Surface Hydrology

Figure 3-3 displays the major drainage basins on the CRL property. Much of the surface drainage from the narrow strip adjacent to the Ottawa River is directly to the river, although Figure 3-3 breaks out the catchment for the Perch Creek, which also discharges to the river.

The Perch Lake Basin contains many of the operating and non-operating waste management facilities, described in Section 1.6. Waste Management Areas A, B, D, G, H, and E as well as the LDA are located in the Perch Lake Basin. Because of this history, this basin is the most affected by past operations. Surface water flows from Perch Lake towards the Ottawa River via Perch Creek.

The proposed NSDF site is adjacent to the Perch Lake wetlands, which occupy most of the low-relief region. These wetlands are a significant feature of the surface hydrology of the Lower Perch Lake Basin to the west and south of the NSDF (see Figure 3-3). The wetland immediately to the west of the NSDF site is called East Swamp, which is connected to Perch Lake via East Swamp Stream and Main Stream. Perch Lake Swamp is located between NSDF and Perch Lake. These wetlands are predominantly forested swamps, which contain small, wetter areas where in some locations shallow open water is present. This area has been impacted by strontium and tritium plumes emanating from legacy waste management operations.

Perch Lake is connected to the Ottawa River via Perch Creek. Figure 3-4 illustrates the Perch Creek catchment areas provided by the 2005 Lidar topography. Most of the NSDF site is within this catchment area.

Between 1966 and 1988 discharge from Perch Lake was measured using a 90^o V-notch weir located at the lake's outlet Figure 3-4. In 1988, the wooden weir box began to fail, and flow measurements at Perch Lake outlet were discontinued. Flow measurements at the Perch Creek weir (Figure 3-4) were initiated in 1984, and this gauging station continues to be used. Over the measurement period, the annual average flow out of Perch Lake was 1.70 x 10^6 m^3/y (Table 3-2) [3-7]. The annual average flow through the Perch Creek weir has been 2.04 x 10^6 m^3/y (Table 3-2) from 1992 to 2016. The difference between these two annual averages is 3.40 x 10^5 m^3/y, which is the annual water input to this reach of Perch Creek.

Table 3-2 Annual Average flows at Perch Lake Outlet and the Perch Creek Weir [3-7]

Location	Measurement Period		Annual Flow
	From	To	(m^3/y)
Perch Lake Outlet	1966	1988	1.70E+06
Perch Creek Weir	1992	2016	2.04E+06
		Difference:	3.40E+05

At CRL, between 1969 and 1980, annual evapotranspiration returned 0.49 m of water from land surfaces to the atmosphere on an annual average basis [3-8]. From 1963 to 2014 (inclusive), annual precipitation at CRL (rainfall plus snowmelt) has averaged 0.845 m (with a range from 0.563 to 1.079 m). The average annual amount of precipitation available for runoff or groundwater recharge (i.e. the difference between rainfall plus snowmelt and evapotranspiration) is, therefore, 0.36 m. Table 3-3 lists the quantities of water entering the segment of Perch Creek between the lake outlet and the weir from the north and south side of the creek, and the total, which is 3.32 x 10^5 m^3/y. The recharge/runoff is derived from the catchment areas and amount of precipitation available for surface water runoff and groundwater recharge. This is 2% lower than the flux into this portion of Perch Creek provided by the weir measurements (3.40x10^5 m^3/y) [3-7]. Perch Creek has a total catchment area of 1 418 400 m^2, and discharges to the Ottawa River at an average rate of 2.21 x 10^6 m^3/y [3-7].

Table 3-3 Recharge into Perch Creek [3-7]

	Area (m^2)	**Recharge/Runoff (m^3/y)**
Perch Creek Upstream Segment Catchment, North	558 900	2.01E+05
Perch Creek Upstream Segment Catchment, South	362 400	1.30E+05
Perch Creek Upstream Segment Catchment, Total	921 300	3.32E+05
Perch Creek Downstream Segment Catchment, Total	497 100	1.79E+05
Perch Creek Total Catchment	1 418 400	5.11E+05
Total Discharge from Perch Creek to Ottawa River		2.21E+06

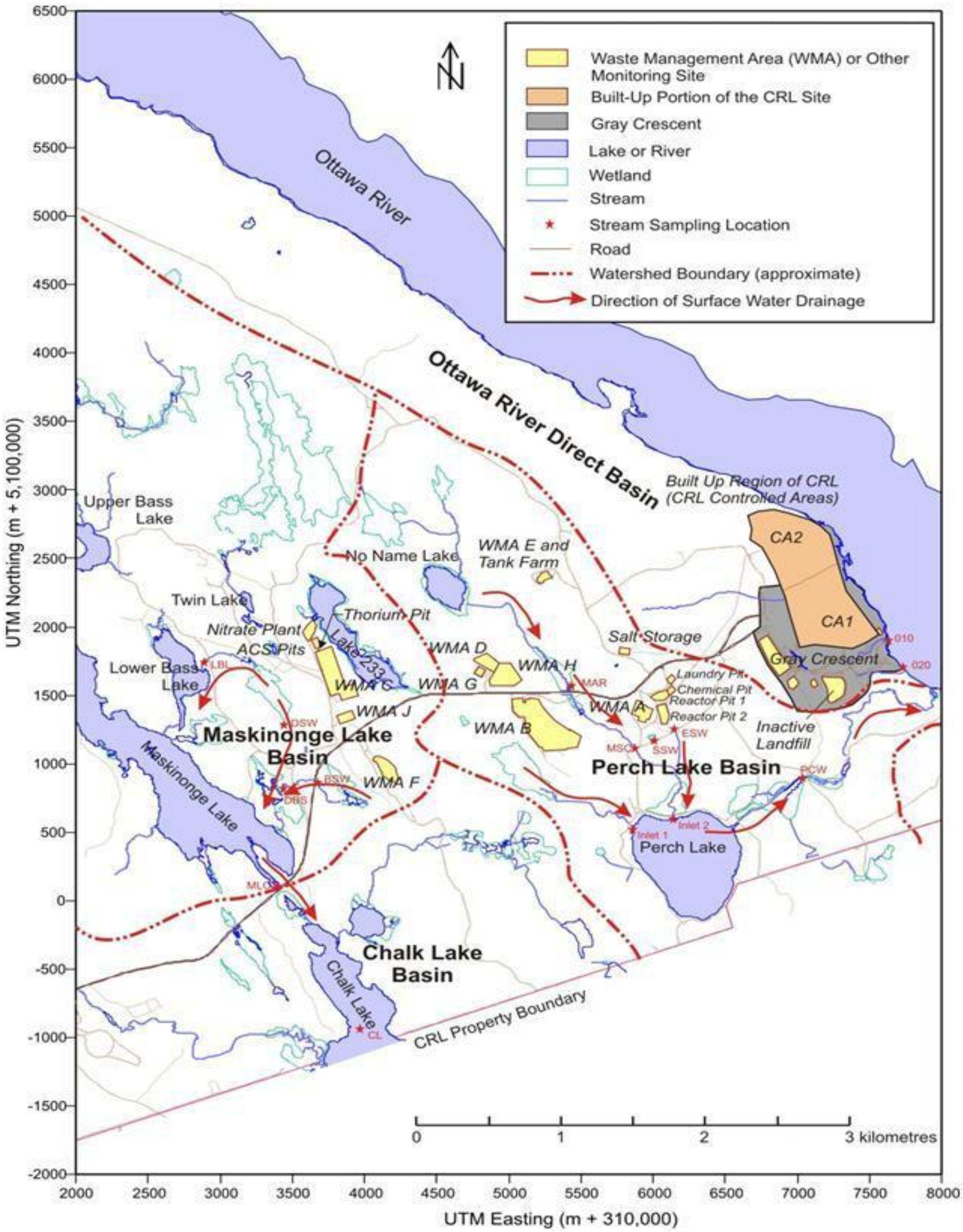

Figure 3-3 Chalk River Laboratories Drainage Basins

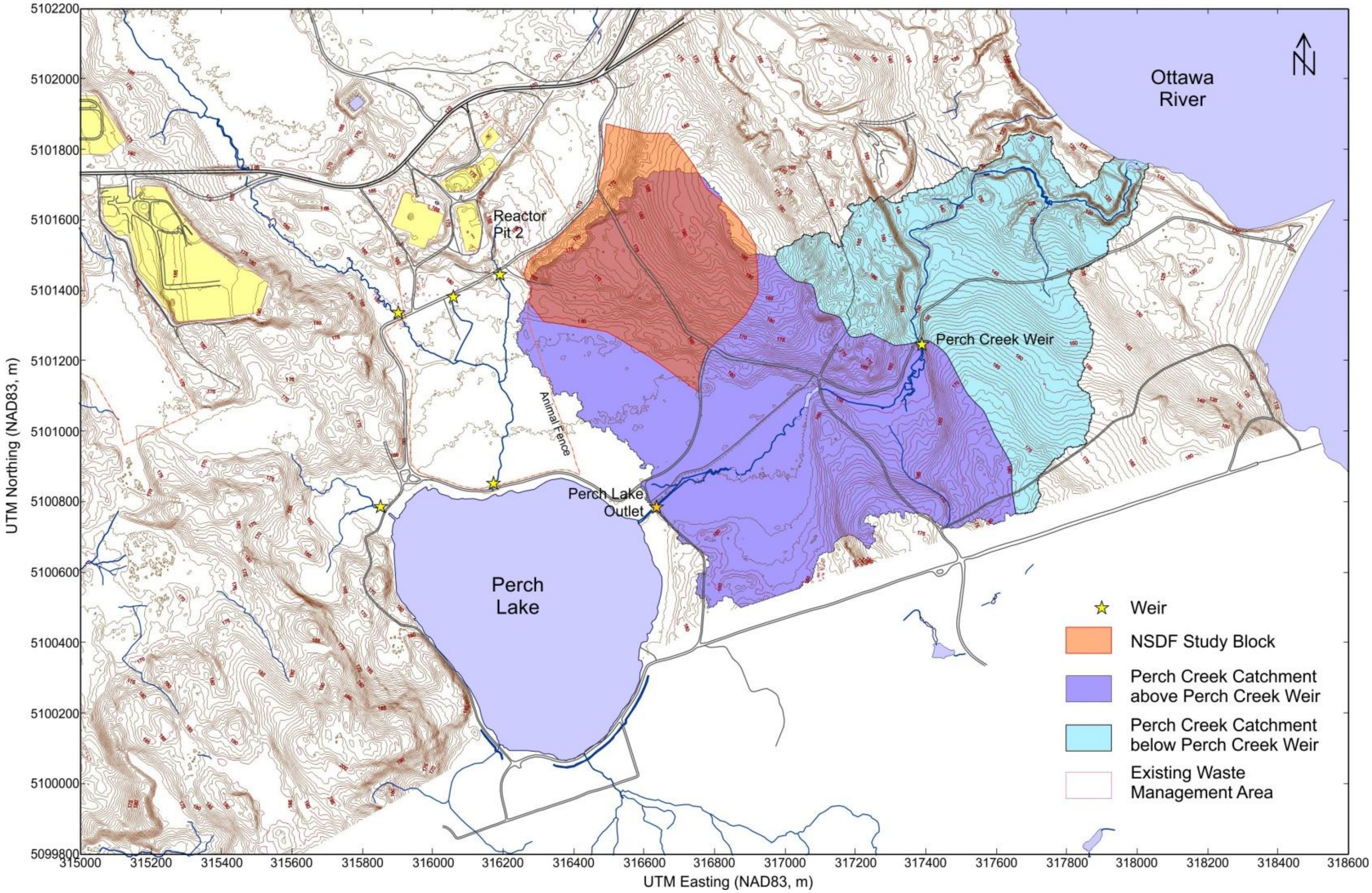

Figure 3-4 Perch Creek Catchment Areas Provided by the 2005 Lidar Topography

3.3 Geology and Seismology

3.3.1 Surficial Geology

The main types of surface cover that are recognized at the Chalk River site are exposed bedrock (18%), till (22%), sand (40%), wetlands (10%), lakes (8%), and sand and gravel (2%).

Glacial till, sediment deposited directly from glacial ice, represents the oldest unconsolidated material at CRL. Local till deposits, which are limited to material deposited by the most recent glaciation, are characteristically massive (i.e. no stratification structures) and poorly sorted (i.e. a very broad range of particle sizes), with the component particles ranging from silt-sized material up to boulders several metres in diameter. Sand is, however, generally the predominant grain size in local till. The till forms a relatively thin cover of unconsolidated sediment over the bedrock on much of the site. In many places, the till is less than 10 m thick, although in depressions in the bedrock surface there are appreciably greater thicknesses of till.

Much of the surficial sediment, and many of the site landforms, are products of the Ottawa River during early stages of deglaciation. Continental glaciers retreated from the Chalk River area, and the Ottawa River initially drained to what is now known as the Upper Great Lakes and, periodically, Lake Agassiz in Manitoba, Saskatchewan and North Dakota. Most of the CRL site, including the Perch Lake Basin, was inundated. As a result, the basin was substantially filled with a series of fluvial deposits. There was a short period following decreases in flow in the Ottawa River and prior to the widespread establishment of vegetation when the fluvial sands and silty sands were re-worked by wind, forming Aeolian sheet deposits and, locally, small dunes.

The overburden thickness at the NSDF site ranges from 0.5 to just over 10 m. The eastern upland area of the site is a bedrock-controlled ridge, with limited bedrock outcrop. Soil on the proposed NSDF site is a Brown Forest Podzol, with a leaf litter and organic mat 5 to 10 cm thick (the A_h horizon) overlying a pale gray leached A_e horizon 2-4 cm thick [3-9]. The underlying B and C horizons are developed in either sand, with thicknesses of up to 5.6 m in the boreholes and test pits in the site footprint, or till in the limited areas where the fluvial and Aeolian sands are absent. There are very limited surface exposures of till, but it is widely presently below the overlying fluvial and Aeolian deposits.

3.3.2 Bedrock

Bedrock on the CRL site consists predominantly of highly metamorphosed gneisses of the Precambrian Grenville province [3-10]. Topography on the CRL site (Figure 3-5) has a pronounced northwest-southeast lineation character, the combined result of faulting in the bedrock associated with the major tectonic feature of the region – the Ottawa-Bonnechere Graben or rift valley – and with fluvial erosion and sediment deposition arising from high flow stages of the Ottawa River in early post-glacial time. The ridges that form the western and eastern boundaries of the Lower Perch Lake Basin are bedrock-controlled, with localized bedrock outcrop, but also frequently feature a thin cover of glacial till and/or fluvial and Aeolian sand. Superimposed on the regional bedrock topography, exposed bedrock surfaces are frequently very irregular, with local relief of several metres over lateral distances of a few to a few tens of metres. Subsurface investigations show that this knobby character is a common feature of buried bedrock surfaces across the CRL site.

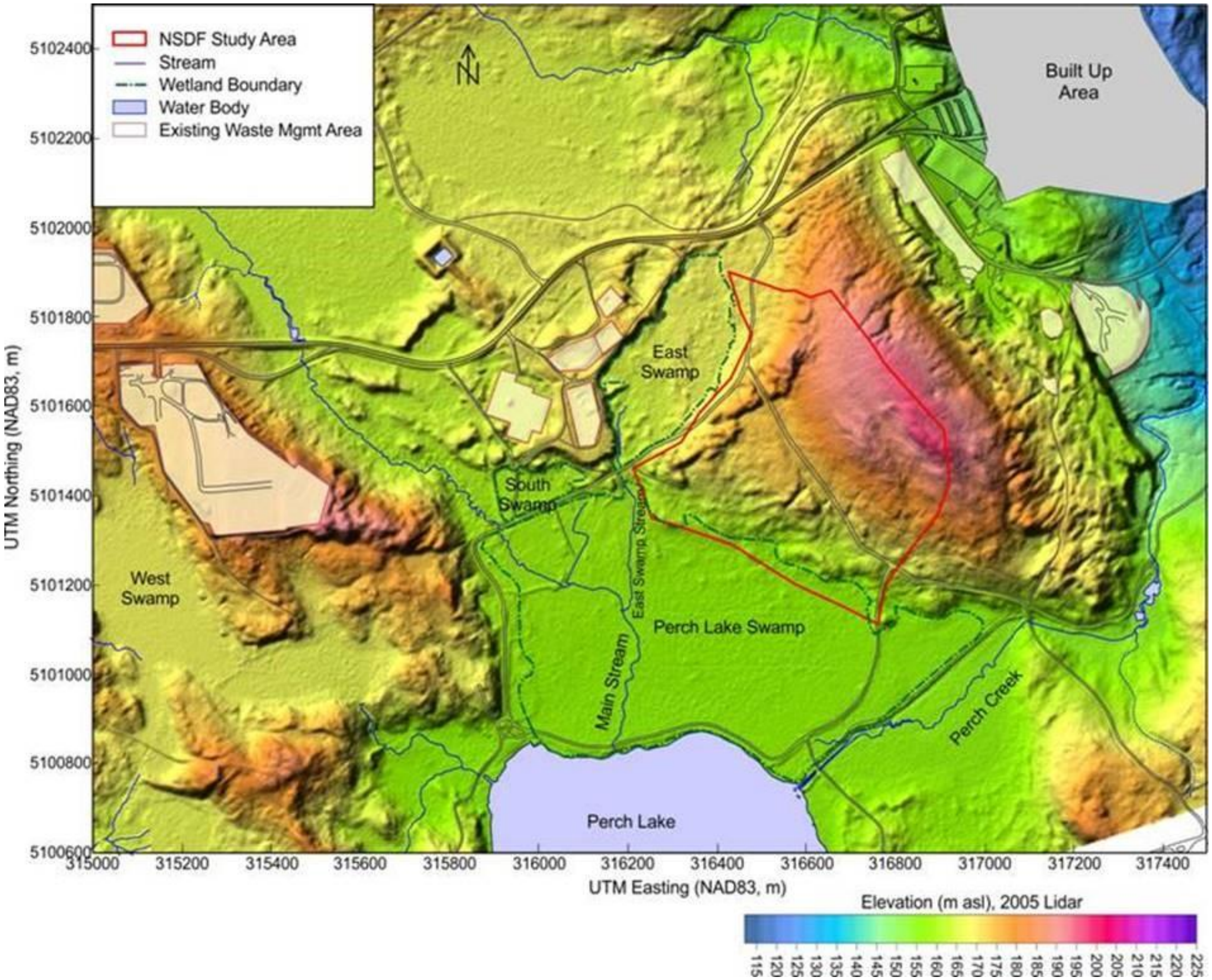

Figure 3-5 Perch Lake Basin Surface Contours

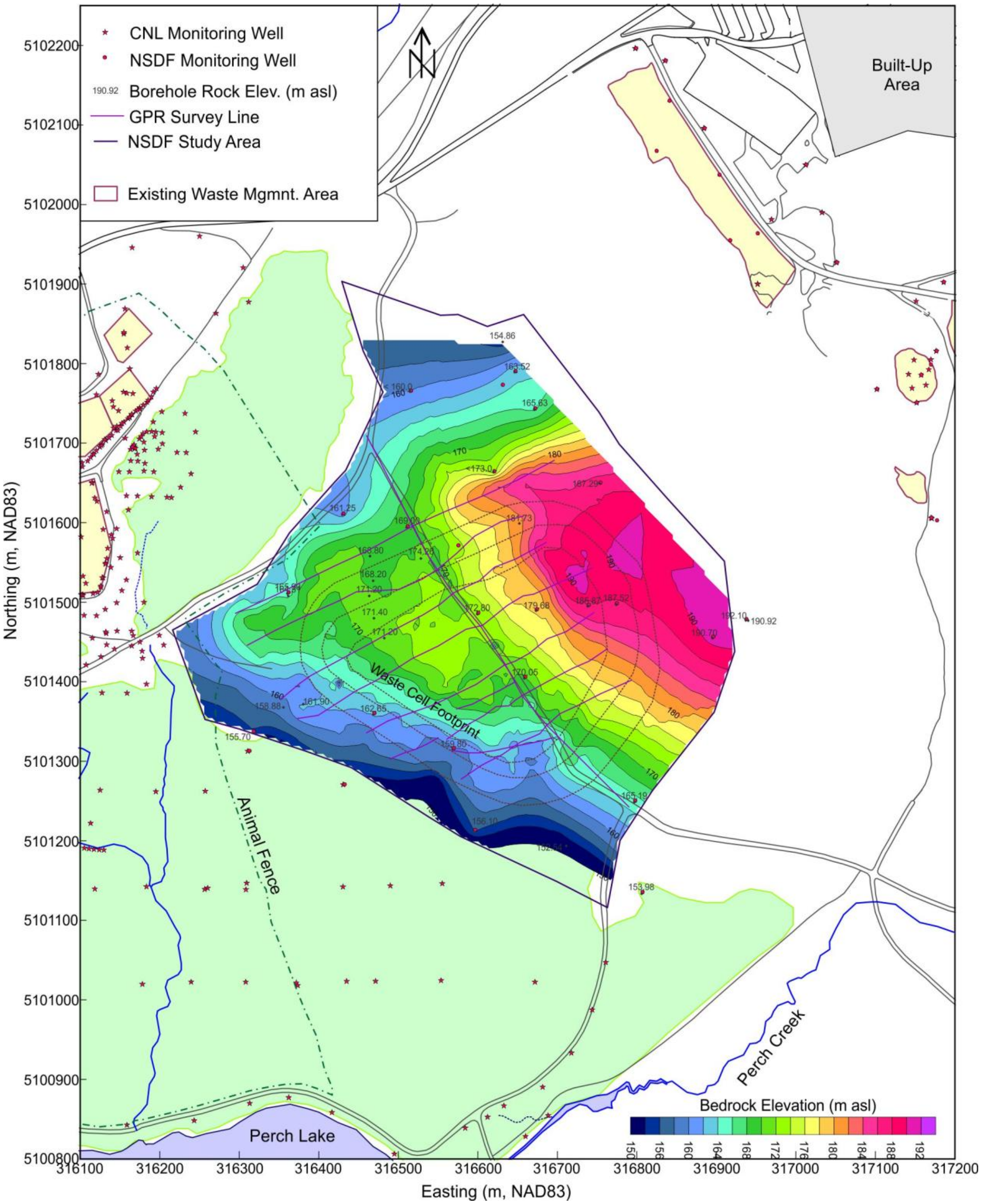

Figure 3-6 NSDF Study Area Bedrock Topography

The bedrock contours of the NSDF site indicate that the buried bedrock surface generally mimics the surface topography and forms a bench along the southwest side of the ridge that defines the eastern limit of the NSDF site. In this area, bedrock occurs at depths of 0.5 m to 4.5 m and Figure 3-7 illustrates the bedrock contours. Field investigations across the CRL site, and within the proposed NSDF study area, have found that the degree of fracturing and fracture interconnections possess substantial spatial variability. Hydraulic conductivities in the bedrock, which are entirely controlled by the fracture network, are consequently also highly variable in both magnitude and in spatial distribution. [3-11] [3-12]

3.3.3 Seismicity

The CRL site is located within the Western Quebec Seismic Zone (WQSZ), where minor seismic activity continues to occur. Low-grade seismicity continues to be observed at or near the CRL site with continuously recording monitoring systems. Ma and Eaton [3-13] analysed the distribution of earthquakes in the WQSZ and concluded that the majority of the zone's seismicity follows the track of the Mesozoic hot spot that gave rise to the Monteregian Hills, with lesser activity associated with the boundary of the Grenville province and with the Ottawa-Bonnechere graben. Within the WQSZ, four significant earthquakes have been detected: in 1732 near Montreal (estimated Richter magnitude 5.8), 1932 in Temiskaming (estimated Richter magnitude 6.2), in 1944 to the south of Cornwall (Richter magnitude 5.6) and most recently, the 2010 earthquake near Val-des-Bois, Québec (Richter magnitude 5.0).

The CRL Design Basis Earthquake (DBE) for nuclear facilities has peak horizontal ground acceleration of 0.257 g, a peak horizontal velocity of 0.136 m/s, and a recurrence frequency of one in 1000 years [3-14]. Unsaturated sands and glacial tills are not considered susceptible to liquefaction under seismic disturbance [3-11] [3-12]. The seismic design basis for the NSDF Seismic Source Characterizations shall be based on the “Operating Instruction Design for Earthquakes Seismic Qualifications at CRL” (AECL 120-508120-OI-029, Rev.1) [3-15]. The National Building Code of Canada (NBCC) [3-16] seismic design criteria shall always be satisfied irrespective of the seismic design basis selected. Additional details on the NSDF Seismic Analysis are provided in [3-17] and [3-18]

3.4 Hydrogeology

Within the ECM footprint, groundwater flow is from the northeast, flowing towards the future location of the south-western berm of the mound. Subsequently it flows south discharging in Perch Creek, which discharges into Ottawa River. Given the groundwater flow patterns, and the location of the ECM relative to Perch Lake and Perch Stream, there is no potential for release to Perch Lake. It is estimated, based on hydrogeological models, that the travel time during pre-closure, from the WWTP outflow to East Swamp, is approximately 3 years. Additionally, the travel time for post-closure, from the ECM to Perch Creek, will be approximately 7-12 year, for the majority of particles. Once radionuclides reach the surface water they are assumed to be quickly transported to the Ottawa River. Further detail on the local groundwater flows can be found in [3-12]. The NSDF section located to the north of the

ECM, including the WWTP wastewater infiltration area, drains west towards East Swamp Stream, from where it is transported through Perch Lake, which feeds Perch Creek. Substances entering the groundwater at the NSDF site are transported through three partly-separate flow systems:

- A shallow aquifer, which discharges to Perch Creek or South Swamp, depending on whether it is in the southern or northern part of the site respectively.
- A middle aquifer that represents most of the permeable material and which flows in the same direction.
- A thin, and likely discontinuous aquifer developed in washed materials on the surface of the till that underlies the fluvio-lacustrine sediments making up the overlying sequence.

The thickness of the unsaturated zone in the footprint of the proposed NSDF facility range are shown in Figure 3-7. In large part, the unsaturated zone thickness in the upland portions of the study area is controlled by the thickness of the sands and till that overlie the bedrock – in the southwest portion of the study area footprint the water table is controlled by the water level in the Perch Lake Swamp. Measurements of hydraulic heads for the region to the west and south of the proposed NSDF footprint have been collected as part of evaluations and monitoring of the groundwater flow system affected by existing waste management areas since the 1960s. Seasonal variations in hydraulic heads and water table elevations have typically been on the order of 1 m, with ranges of up to 2 m in recharge areas and smaller variations in portions of the flow system adjacent to or below wetlands, where surface water levels are the primary control on subsurface heads. Hydraulic head data for the proposed NSDF region have been collected in 2016 as part of the characterization of the proposed site. Figure 3-7 displays point values of water table elevations in and immediately adjacent to the study area footprint for 2016 December and contours of the water table generated from these point measurements and from average water table elevation data for portions of the flow system downgradient of the study area.

A numerical model of groundwater flow in the lower Perch Lake basin has been developed (e.g. [3-12]). Figure 3-7 displays simulated water table contours along with the differences between observed and simulated water table elevations. Hydraulic gradients (the change in hydraulic head over the distance between measurement locations) within the study area for the proposed NSDF facility are up to 0.10. Over the groundwater flowpath between the NSDF study area and Perch Creek, however hydraulic gradients decrease to approximately 0.006.

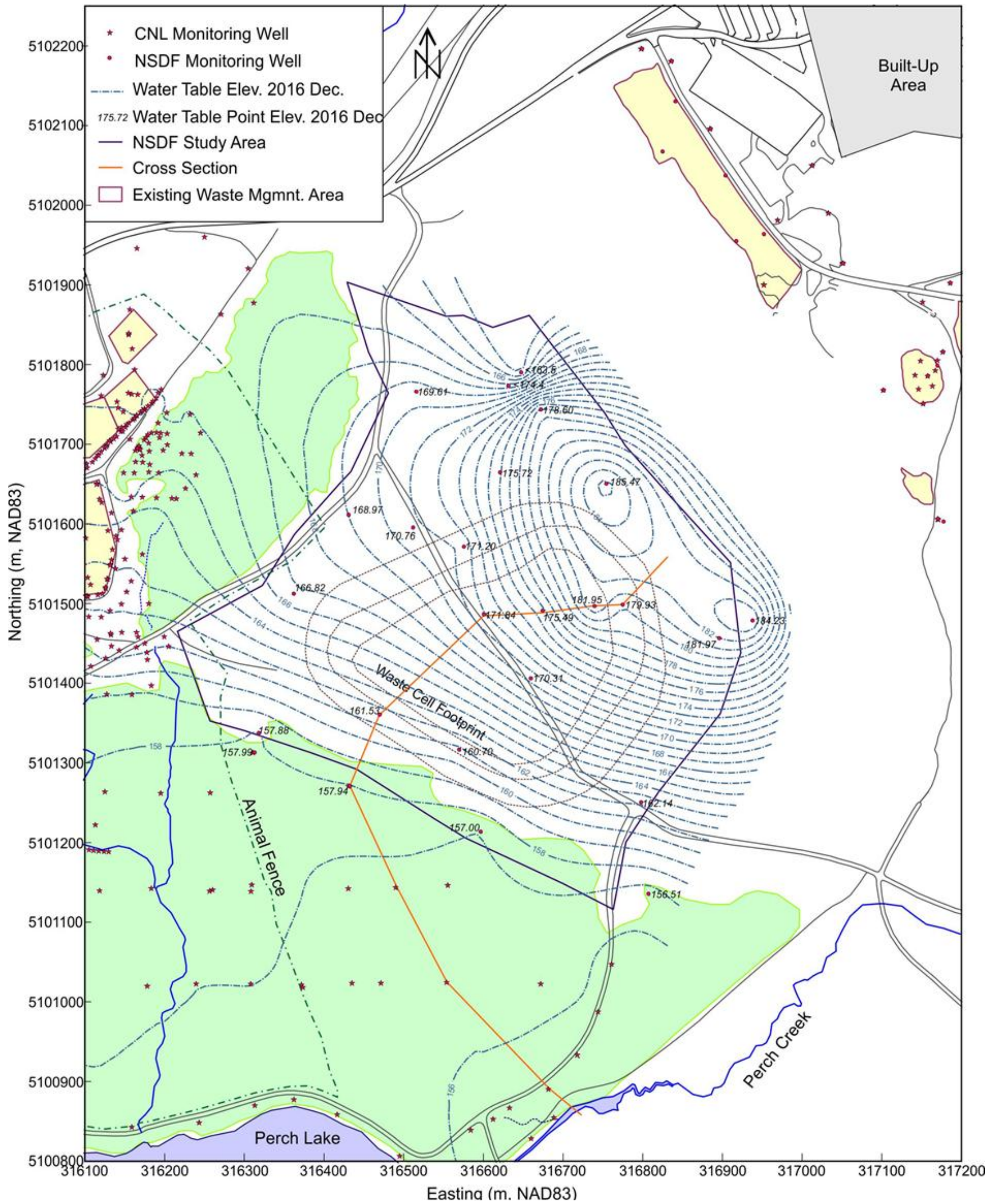

Figure 3-7 Groundwater Contours at the NSDF Site

Comprehensive networks of groundwater monitoring wells, located throughout the CRL site, provide information on groundwater quality, water table elevation, shallow groundwater gradients, and flow paths at CRL. Hydraulic properties governing groundwater flow and velocity are hydraulic conductivity (the permeability of the subsurface material with respect to water) and porosity. Table 3-4 provides a summary of the hydraulic conductivity measurements and estimates for hydrostratigraphic units in the lower Perch Lake Basin [3-11].

Table 3-4 Hydraulic Properties of Geologic Materials

Hydrostratigraphic Unit	Hydraulic Conductivity (m/s) (geometric mean)	Porosity
Fine sand	2.0E-05	0.36
Clayey silt	1.9E-08	0.45
Silty sand	4.9E-07	0.35
Stony sand till	6.26E-07	0.30
Crystalline bedrock	1.7E-07	0.01

The stratigraphy and vertical hydraulic head distribution along the cross-section from the NSDF site to Perch Creek is shown in Figure 3-8.

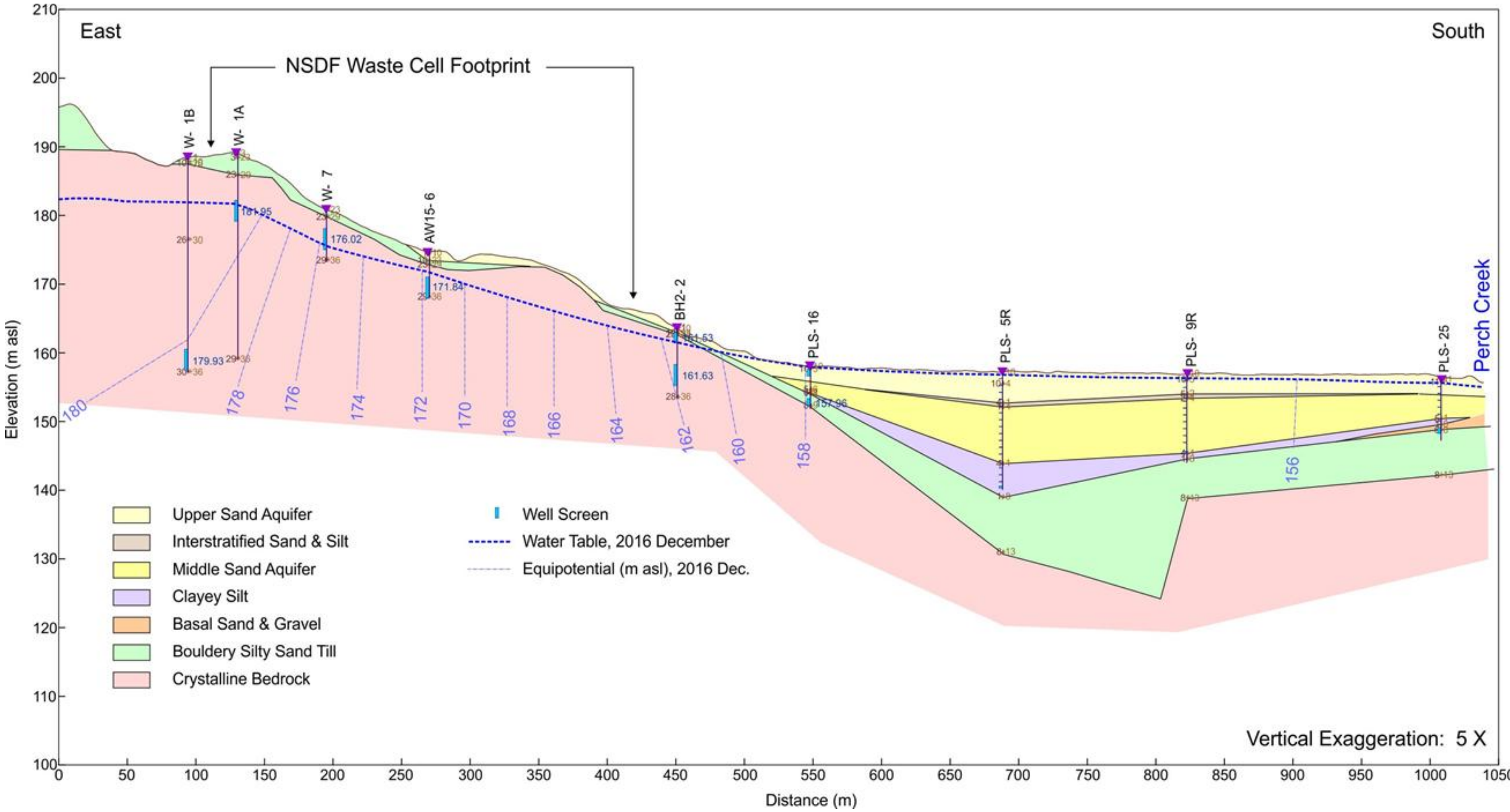

Figure 3-8 Stratigraphic Cross Section from the NSDF site to Perch Creek [3-19]

Distribution coefficients (K_d) represent the partitioning of a compound from one media to another. Distribution coefficients are used in subsequent pre and post-closure assessments (Sections 7 and 8). Chalk River site-specific groundwater distribution coefficients were derived in mid 1990s [3-20]. These are presented in Table 3-5.

Table 3-5 Site Specific K_d [3-20]

Radionuclides	Site specific K_d (cm^3/g)
Ac-227[1]	20
Ag-108m[2]	95000
Am-241	1900
Am-243	1900
C-14	5
Cl-36	0
Co-60	60
Cs-135	280
Cs-137	280
H-3	0.06
I-129	1
Mo-93[2]	100
Nb-93m	750
Nb-94	750
Ni-59	400
Ni-63	400
Np-237	5
Pa-231[2]	5400
Pb-210	270
Po-210[1]	10
Pu-239	550
Pu-240	550
Pu-241	550
Pu-242	550
Ra-226	500
Ra-228	500
Se-79	26
Sn-126	130
Sr-90	13

[1] K_d values for Ac-227 and Po-210 are the default values from RESRAD

[2] K_d values for Ag-108m, Mo-93, Pa-231, and Zr-93 are from CSA N288.1-14.

Radionuclides	Site specific K_d (cm^3/g)
Tc-99	0.1
Th-228	3200
Th-229	3200
Th-230	3200
Th-232	3200
U-233	35
U-234	35
U-235	35
U-236	35
U-238	35
Zr-93[2]	1000

3.5 Groundwater Monitoring Results

Canadian Nuclear Laboratories has performed extensive studies of the flow of water into the Perch Lake Basin for many years. Overall data description from these studies is provided in the NSDF EIS (Section 5.3.2.4.2.2). Of particular relevance to the proposed NSDF is the existence of site specific data on radionuclide migration and retardation in the Perch Lake Basin.

Thus, Figure 3-9 shows the groundwater tritium plume emanating from the Reactor Pit 2 at the upper sand aquifer [3-19]. As tritium moves at essentially the velocity of groundwater (K_d=0.06 cm^3/g, see Table 3-5), it acts as an excellent tracer to evaluate transit times between the Reactor Pit 2 and Perch Lake/Perch Creek. Plume mapping studies determined that the leading edge of tritium contamination from Reactor Pit 2 arrived at Perch Creek in less than 24 years.

However, other contaminants do not move at the same rate as water. Strontium distribution coefficients (k_d) measured on Perch Lake Basin sand average between 6 and 9 cm^3/g [3-21]. With a k_d of 6.2 cm^3/g, Sr-90 (note that the variation between this value and the one presented in Table 3-5 is within natural variation) would move through the groundwater flow system at 3.7% of the velocity of the neutral components [3-19]. For Cs-137, typical velocities through the sandy aquifer in the Lower Perch Lake Basin are about 0.3% of groundwater velocity [3-19]. Accordingly, transit times for these radionuclides through the Perch Lake Basin would be considerably longer than those for tritium.

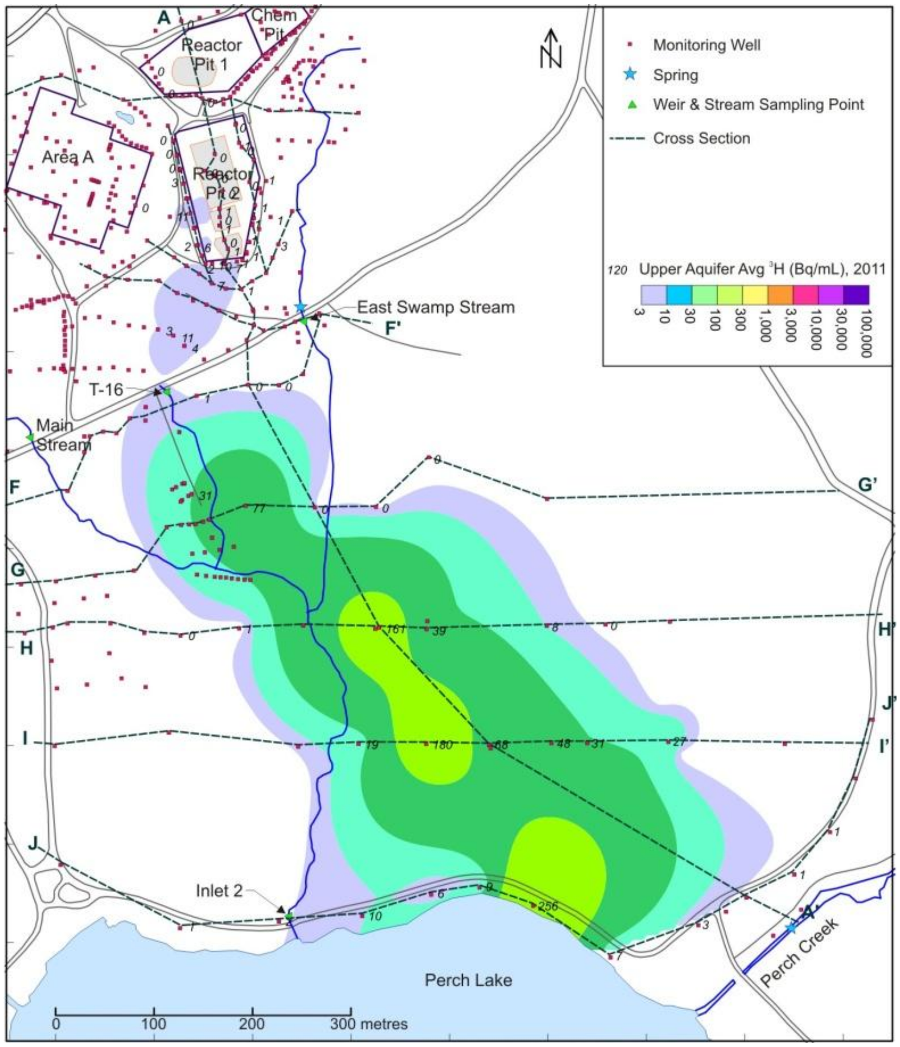

Figure 3-9 Groundwater Tritium Concentrations in the Upper Sand Aquifer

Note: Groundwater model was calibrated using historical empirical data. See [3-12] for additional detail.

3.6 Climate

3.6.1 Current Conditions

The climate of the area is classified as humid continental, with warm summers, cold winters, and no distinct dry season. In quantitative terms, based on data collected at CRL since 1963 [3-1]:

- The daily mean air temperature ranges from -12°C in January to 19°C in July, with historic minima and maxima of -39°C and 39°C.
- Annual precipitation has ranged from 560 mm to 1 080 mm of water equivalent, with an average of 845 mm over the period 1963 to 2015. Over this period, monthly precipitation

has averaged 44 mm in February to approximately 86 mm per month during the June to September, inclusive. On average, 23 percent of the annual precipitation falls as snow.

Hydrologic studies in the Perch Lake Basin over the period between 1969 and 1980, determined that evapotranspiration accounted for the annual return of 530 mm of precipitation to the atmosphere, while lake evaporation returned 690 mm to the atmosphere. The freezing index at the CRL site is 1 164 degree-days (each degree below 0°C in mean outdoor temperature, averaged over a 24 hour period, is a degree-day).

3.6.2 Climate Change

General circulation models have inherent limitations that are important to bear in mind when evaluating variability and the rate of climate change, (i.e. when comparing future projections to historical observations). These limitations are dependent on the research institution's approach to overcoming model uncertainty. Since no one model or climate scenario can be viewed as completely accurate, the Intergovernmental Panel on Climate Change recommends that climate change assessments use as many models and climate scenarios as possible. For this reason, the multi-model ensemble approach described above was used to account for these uncertainties and limitations.

The EIS, (Section 10) for the NSDF will indicate that, in the short to medium term, prior to the NSDF closure in 2100, the climate will be warmer and slightly wetter than it is today [3-4]. This may involve increases in average annual temperature of up to 2 - 3°C and increases in precipitation of about 10% from the current levels. Such changes may accelerate erosion of the engineered cover. The increase in precipitation will be counteracted by increases in evapotranspiration, thus, resulting in only minor impacts on recharge, leaching and local hydrology.

The frequency of extreme events such as extreme rain, is predicted to increase, although, the magnitude of bounding events is unlikely to be impacted. Again, this may lead to accelerated erosion of the engineered cover.

Global warming is projected until the year 3000 (up to about 8 °C over 1000 years). This represents a much higher warming rate than that seen at the end of the last glacial period and corresponds to a higher rate of increase in atmospheric CO_2 concentrations than in previous periods. It is therefore expected that there will be a relatively long interglacial period so that the next glaciation cycle is not likely to occur for at least 100,000 years [3-22]. It is predicted that a glacier will cover the territory of Ontario, which includes the NSDF location, for tens of thousands of years [3-21].

3.7 Wind Speed and Direction

The metrological tower at Perch Lake has been collecting wind data since 1983 from anemometers installed at 60 m and 30 m. Wind conditions at 60 m reflect the CRL reactor exhaust stack, while the 30 m data better reflect the conditions at the NSDF site.

The distributions of wind speeds and directions show little seasonal or annual variability. The winds at CRL are predominantly northwest and southeast (parallel to the Ottawa River Valley) [3-23]. Figure 3-10 illustrates the windrose at the 30 m height from Perch Lake tower.

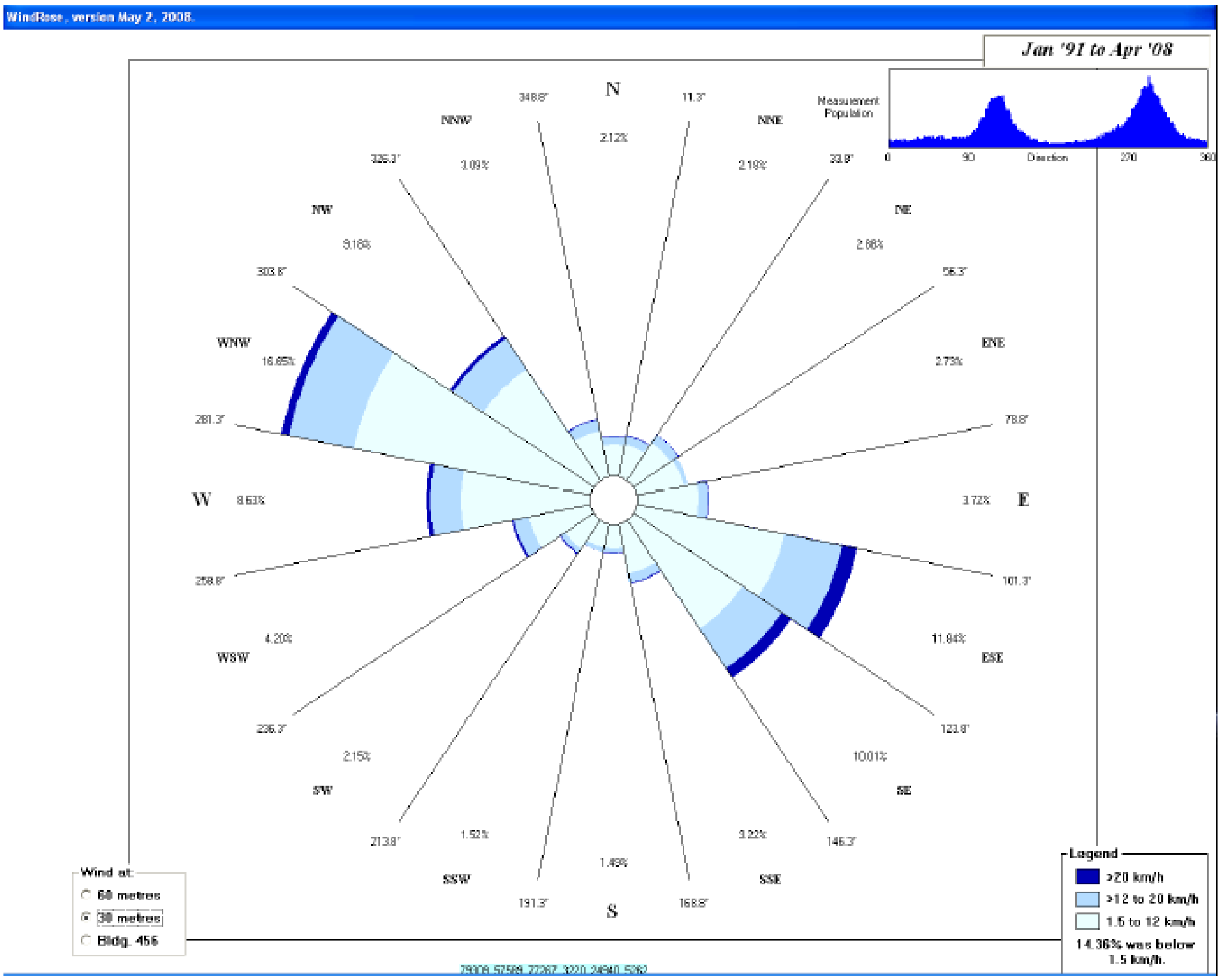

Figure 3-10 Wind Rose Diagram - Perch Lake 30 m (1991 January to 2008 April)

3.8 Extreme Meteorological Events

Extreme weather conditions, which may impact long-term performance of the NSDF, include extreme precipitation (rainfall and snowfall) and extreme winds.

3.8.1 Extreme Precipitation

Rainfall is measured twice per day and at more frequent, irregular intervals during heavy rain. The highest rainfall recorded at CRL in a 24 hour period (since 1963) was 70.2 mm in the 24 hours of 2002, June 11 [3-1].

There is a finite limit on the atmosphere's ability to produce rain at any given location dictated by the climate, topography and atmospheric moisture limit. The concept of a finite limit for precipitation from a single storm event is called the Probable Maximum Precipitation (PMP). Probable Maximum Precipitation is a more useful metric for understanding the maximum amount of water that could be present on or near the NSDF at a single time. Probable Maximum Precipitation is defined as the greatest depth of precipitation for a given duration meteorologically possible for a given size storm area at a particular location, particular time of year, with no allowance made for long-term climatic trends [3-24] and [3-25].

The Lakes and Rivers Improvement Act [3-26], provides the current Provincial Requirements for a PMP hazard in Ontario (see Table 3-6).

Table 3-6 Probable Maximum Precipitation Estimates

Storm Duration (hours)	Total Rainfall (mm)
48	460
36	445
24	440
12	420
6	405

For watershed areas, less than 1 300 km^2, a 6 or 12 hour PMP duration is normally used for flood risk assessment, as these usually produce the highest peak flood flow.

The Probable Maximum Flood for the CRL site is calculated to be 130.1 m [3-1]. The NSDF site has elevations ranging from a low of approximately 160 mASL to a 196 mASL. The scenario that produces the maximum flood is a 1:100 year snow accumulation and PMP from a storm. The analysis concludes that it would be appropriate to assign the annual probability of this event occurring at CRL as 10^{-7}.

3.8.2 High Wind

High winds can occur either on a large scale from extra-tropical storms or low pressure systems and fronts or on a small scale, from thunderstorms, or the local geography.

High winds generally fall into three categories:

- Thunderstorm winds.
- Extra-tropical storms (hurricanes).
- Tornadoes.

High winds and, wind gusts, can cause damage to structures either due to wind pressure or due to impacts by loose items ("missiles") becoming airborne.

Only thunderstorm winds and tornadoes are relevant to the NSDF site. Hurricanes do not generally impact locations which are more than a few hundred kilometers from the ocean. The Fujita scale (F0-F5) is currently applied in Canada but was discontinued in the US in 2007 and replaced by the Enhanced Fujita scale. Environment Canada is currently considering implementation of the Enhanced Fujita Scale. This scale takes into account the quality of construction and standardizes different kinds of structures.

Chalk River Laboratories Site Characteristics Document [3-1] describes the analyses of the CRL site location with respect to Tornado Climatology of the Contiguous United States, NUREG/CR-4461, Revision 2. Chalk River Laboratories exists in a geographical area that could reasonably expect a 10^{-5}/y tornado strike event. The maximum wind speed for a 10^{-5}/y tornado event is 225 km per hour.

3.8.3 Lightning

The region around CRL experiences roughly 22 days with thunderstorms each year. Lightning frequency is calculated as the average number of flashes per 100 km^2. Ottawa experiences 90 flashes per 100 km^2, and Thunder Bay experiences 36 per 100 km^2 [3-1].

The NSDF site is located on the side of a hill and in a valley, which tends to reduce the frequency of direct lightning strikes.

3.8.4 Severe Ice Storm

The Ottawa Valley is particularly prone to freezing rain because the valley tends to trap cold air; typically, it receives freezing rain on 12 to 17 days per year, for an annual average of 45 to 65 hours [3-27].

A severe ice storm in the CRL area is an infrequent event, occurring with an approximate frequency of 1.0×10^{-2}/y, or one occurrence per 100 years. A severe ice storm could result in the loss of Class IV power for an extended period of time.

3.9 Ecology

The following sections discuss the plant and animal species and communities that may be found on the CRL site, including threatened, endangered and sensitive species.

3.9.1 Habitats

Wetlands on the CRL Site: Wetlands on the CRL site and in particular the Perch Lake wetland could be considered Valued Components (VCs). Wetlands support a wide diversity of flora and fauna. The Perch Lake wetland is considered to be provincially significant in the context of northern wetlands, according to the Ministry of Natural Resources Northern Wetland Evaluation Protocol. The wetland is located in the Perch Lake Basin between the Plant Road and Perch Lake. Wetland areas are located to the south and west of the NSDF site (Figure 3-11), with a minimum of 30 m setback. Flora characteristic to wetland areas can be subdivided into communities associated with “swamp” and “marsh” areas.

Wetland Communities - Swamps: Deciduous swamp communities are comprised mainly of speckled alder shrubs and trees, black ash and red maple. Coniferous communities are typically dominated by black spruce, or less commonly, by white cedar. The Perch Lake wetland just south of the NSDF site and the South Swamp to the west are classified as swamps, which are wooded wetlands.

Wetland Communities - Marshes: Marshes are dominated by shrubs or herbaceous and graminoid (grass-like) species. Permanently flooded areas support a range of robust emergents and aquatic free-floating and submerged plants. The wetland surrounding Perch Creek is classified as a Marsh.

Forest: The forest surrounding the proposed NSDF site supports a diverse wildlife habitat, including several species at risk which are described further.

3.9.2 Valued Components

Part of CRL's environmental impact review is to consider these impacts on a sub-set of environmental components that have been identified as sensitive and important to local and scientific communities. A sub-set of environmental values, known as VCs, is included in this document and requires special attention as CRL carries out its operation of the NSDF. As there are hundreds of species of vertebrates and likely tens of thousands of invertebrate species in Ontario, a species-by species approach for the conservation of biodiversity is impossible. For the purpose of this case, a VC is a sensitive component of the environment, requiring special consideration while assessing the impact of disturbances of the NSDF site to ensure that risks to populations of non-human biota are minimized. In the context of the PA, doses to a range of indicator species will be assessed for Pre- and Post-closure periods. In order to evaluate potential ecological risks, it is necessary to ensure that VCs are represented by indicator species at similar trophic levels and with similar habits.

There is an on-going biodiversity study being implemented at the NSDF site [3-28]. As new information is provided on ecosystems, habitats and species, and as societal values change, this analysis will be updated to reflect that new information. If warranted, new management and monitoring strategies will be developed (Species at Risk Permit # 831).

A list of proposed VCs was developed from those that are documented to occur in the vicinity of the NSDF site, have potential for exposure, play a key role in the food web, and represent a variety of habits and trophic levels [3-28]. In order to determine the potential effect of radiological emissions on the environment, a smaller group of indicator species was chosen to represent VCs selected for assessment. Indicator species were chosen based on at least one of the following criteria:

- They are reflective of the main exposure pathways, feeding habits, habitats, etc. on the site, and particularly those associated with the highest exposures.
- They are known to reside on the site, and therefore, are potentially exposed to environmental effects from the NSDF.
- Represents a major plant or animal group.
- They are representative of their trophic level, resulting in representation for all trophic levels and therefore, all exposure pathways.
- They are particularly sensitive to stressors.

- They occupy a unique niche in their habitat or have a unique diet.
- They are ecologically significant (e.g. classified as Species at Risk).
- They have a special socio-economic importance or value, e.g. due to their economic value or cultural importance.

Table 3-7 shows wildlife and plant species in the area that may be affected by the project with VCs and indicator species identified. In addition to species presented in the table, worms were selected as an indicator species to represent soil quality and crayfish was selected as an indicator species (Effects Exposure – E) to represent sediment quality.

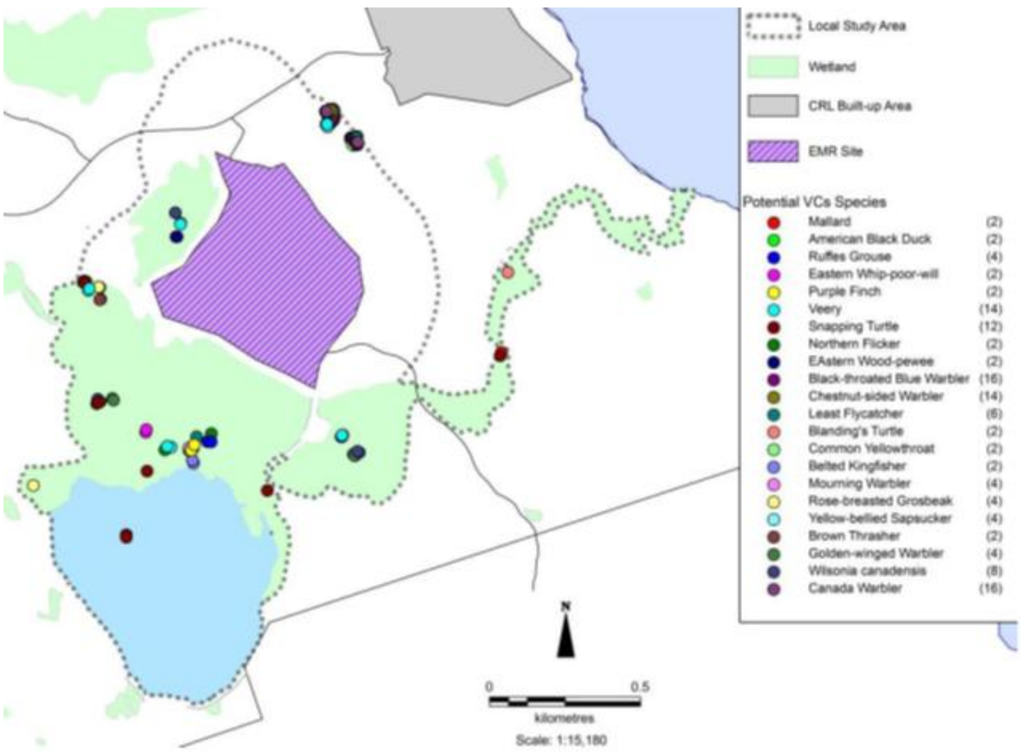

Figure 3-11 Habitat Areas of Potential Valued Components [3-28]

Table 3-7 List of Wildlife and Plant Species in the Potentially Affected Area

Environmental Component	Taxa	Category	VCs		Effects Habitat (H) Exposure (E)	Indicator species	Justification for Inclusion in Exposure Assessment
			Population group or habitat type	Species at Risk or Regional Rare Species			
Aquatic environment	Fish	Small - Pelagic forage (omnivores)	Fish and Fish Habitat	Bluntnose Minnow Common Shiner Creek Chub Pumpkinseed Blacknose Shiner Fathead Minnow Pearl Dace	H, E	Bluntnose minnow	Present in Perch Creek, represents small pelagic fish
		Small – Benthivorous	Fish and Fish Habitat	Johnny Darter Brown Bullhead Black Bullhead Longnose Dace	H, E	Black Bullhead	Present in Perch Creek, represents small benthivorous fish
		Large - Benthivorous	Fish and Fish Habitat	Lake Sturgeon White Sucker	H, E	Not applicable[1]	Not present in the local study area, where surface water concentrations are higher than in the Ottawa River

Environmental Component	Taxa	Category	VCs		Effects Habitat (H) Exposure (E)	Indicator species	Justification for Inclusion in Exposure Assessment
			Population group or habitat type	Species at Risk or Regional Rare Species			
Aquatic environment	Fish	Small - Carnivorous	Fish	Logperch Fallfish Yellow Perch Mottled Sculpin	H, E	Not applicable[1]	Not present in the local study area, where surface water concentrations are higher than in the Ottawa River
		Large - Carnivorous	Fish	Northern Pike	H, E	Pike	Present in Perch Lake, represents Large Carnivorous fish
Terrestrial Environment	Plant	Aquatic	Vegetation Communities		E	Reed (Food for predators)	Present in the wetlands in the Local Study Area, represents aquatic vegetation communities, foodchain
		Terrestrial	Vegetation Communities		E	Red Maple	Present in the Local Study Area, represents terrestrial vegetation communities

Environmental Component	Taxa	Category	VCs: Population group or habitat type	VCs: Species at Risk or Regional Rare Species	Effects Habitat (H) Exposure (E)	Indicator species	Justification for Inclusion in Exposure Assessment
Terrestrial Environment	Insect	Pollinator		Monarch Butterfly	E	Monarch Butterfly	Present in the Local Study Area, represents Pollinators
	Mammals	Small - Insectivores	Bats	Little brown Myotis Eastern small-footed Myotis Northern Myotis Tri-coloured Bat	H, E	Little brown Myotis	Present in the Local Study Area, represents small insectivores
		Small - Herbivore			E	Meadow Vole	Present in the Local Study Area, represents small herbivores mammals
		Large - Herbivore			E	White-tailed deer	Present in the Local Study Area, represents large herbivores mammals, public interest
		Small - Omnivorous			E	Short-tailed Shrew	Present in the Local Study Area, represents small omnivorous mammals

Environmental Component	Taxa	Category	VCs		Effects Habitat (H) Exposure (E)	Indicator species	Justification for Inclusion in Exposure Assessment
			Population group or habitat type	Species at Risk or Regional Rare Species			
Terrestrial Environment	Mammals	Large - Omnivorous			E	Black Bear[2]	Present in the Local Study Area, represents large omnivorous mammals, public interest
		Large - Carnivorous		Eastern Wolf	E	Eastern Wolf	Present in the Local Study Area, represents large carnivorous mammals, public interest
	Reptile	Semi-terrestrial	Turtle	Blanding's Turtle Snapping Turtle	H, E	Snapping Turtle	Present in the Local Study Area, represents semi-terrestrial reptiles (turtle)
		Semi-terrestrial	Snake		E	Common Watersnake	Present in the Local Study Area, represents semi-terrestrial reptiles (snake)
		Terrestrial	Snake		E	Eastern Milksnake	Present in the Local Study Area, represents terrestrial reptiles (snake)

Environmental Component	Taxa	Category	VCs		Effects Habitat (H) Exposure (E)	Indicator species	Justification for Inclusion in Exposure Assessment
			Population group or habitat type	Species at Risk or Regional Rare Species			
Terrestrial Environment	Amphibian	Semi-aquatic	Frog		E	Green Frog	Present in the wetlands in the Local Study Area, represents semi-aquatic amphibians
	Bird	Small – Insectivores	Migratory birds	Wood Thrush Veery Eastern Wood-pewee Black-throated Blue Warbler Least Flycatcher Chestnut-sided Warbler Common Yellowthroat Mourning Warbler Brown Thrasher Golden-winged Warbler Canada Warbler	H, E	Canada Warbler	Present in the Local Study Area, represents small insectivores birds
		Large Insectivores		Eastern Whip-poor-will Yellow-bellied Sapsucker	H, E	Eastern Whip-poor-will	Present in the Local Study Area, represents large insectivores birds
		Small Omnivores		Purple Finch Rose-breasted Grosbeak White-throated Sparrow	E	Purple Finch	Present in the Local Study Area, represents small omnivores birds

Environmental Component	Taxa	Category	VCs		Effects Habitat (H) Exposure (E)	Indicator species	Justification for Inclusion in Exposure Assessment
			Population group or habitat type	Species at Risk or Regional Rare Species			
Terrestrial Environment	Bird	Large Omnivores		Northern Flicker Ruffed Grouse	E	Ruffed Grouse	Present in the Local Study Area, represents large omnivores birds
		Small Carnivores		Belted Kingfisher	E	Belted Kingfisher	Present in the Local Study Area, represents small carnivores omnivores birds
		Large Carnivores	Raptors	Bald Eagle	E	Bald Eagle	Present in the Local Study Area, represents large carnivores omnivores birds, public interest
		Small semi-aquatic	Waterfowl	American blackduck Mallard	E	Mallard	Present in the Local Study Area, represents small semi-aquatic birds, public interest

Environmental Component	Taxa	Category	VCs		Effects Habitat (H) Exposure (E)	Indicator species	Justification for Inclusion in Exposure Assessment
			Population group or habitat type	Species at Risk or Regional Rare Species			
		Large semi-aquatic		Great Blue Heron	E	Great Blue Heron	Present in the Local Study Area, represents large semi-aquatic birds, public interest

1 Not applicable as species is not bounding for Performance Assessment.
2 Could be excluded from Performance Assessment as species has a very large home range.

In addition to Indicator Species identified, two additional Indicator Species were selected for Exposure Assessment as follows:

- Benthic Invertebrates (Worms) as indicator species for soil quality.
- Crustaceans (Crayfish) as indicator species for sediment.

3.10 References

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4. NEAR SURFACE DISPOSAL FACILITY WASTE INVENTORY

This section summarizes the physical and radiological characteristics of the wastes to be emplaced in the NSDF. The purpose of the NSDF is to contain and dispose as much of the waste arising from past, present and future operational, decommissioning and commercial activities, provided they meet the WAC. Acceptable waste categories have been defined to ensure the long-term safety of the workers, public and the environment.

A conservative estimate of waste inventory is presented below. This estimate was extrapolated from the available data on the waste currently in storage, and conservatively overestimates the radioactivity levels of future waste streams, which will be dominated by lower-concentration radioactive materials generated from decommissioning and environmental remediation work. Basing the PA on this inventory ensures that potential consequences are evaluated in a conservative manner.

4.1 Waste Categories and Volumes

The NSDF will dispose of LLW and other suitable waste streams that meet the WAC, as follows:

1. Low Level Waste

Low Level Waste is defined as follows:

- **International Atomic Energy Agency, GSG-1**: "Waste that is above clearance levels, but with limited amounts of long lived radionuclides. Such waste requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near surface facilities. This class covers a very broad range of waste. Low-Level Waste may include short lived radionuclides at higher levels of activity concentration, and also long lived radionuclides, but only at relatively low levels of activity concentration" [4-1].
- **Canadian Standards Association: N292.0-14**: "Low-level Waste contains material with radionuclide content above established clearance levels and exemption quantities, but generally has limited amounts of long-lived activity. For orientation purposes only, a limit of 400 Bq/g on the average (and up to 4 000 Bq/g for individual packages) for long lived alpha emitting radionuclides can be considered in the classification process. For long lived beta and/or gamma emitting radionuclides, such as C-14, Ni-63, Zr-93, Nb-94, Tc-99, and I-129, the allowable average activity concentrations can be considerably higher (up to tens of kBq/g) and can be specific to the site and disposal facility. Low-Level Waste does not generally require significant shielding during handling and interim storage" [4-2].

These two definitions of LLW, while not identical, provide a consistent framework and encompass waste streams containing predominantly short lived radionuclides as well as limited quantities of long-lived isotopes. The CSA definition, furthermore, clarifies that LLW can generally be safely handled and stored without significant shielding.

Examples of LLW include contaminated items such as paper, cardboard, wood, plastic sheeting, protective clothing, scrap metal redundant equipment, process wastes, filters, and excavated soil. Typically, LLW does not require shielding.

2. Intermediate-Level Waste

Intermediate-Level Waste contains higher quantities of long-lived radionuclides and may require shielding to ensure that it can be handled and stored in a safe manner. Intermediate-Level Waste does not include waste streams incorporating used fuel and reprocessing products, generating over 2 kW/m^3 of heat, which are classified as HLW. Only ILW streams that can be disposed in a near surface facility, in such a manner that safety objectives can be met will be accepted at the NSDF.

Examples of suitable ILW waste streams may include short lived higher activity waste requiring shielding, immobilized liquid effluent from CRL operations, and ion exchange (IX) resins.

3. Total Waste Volumes and Waste Streams

The volumes of the NSDF waste have been estimated in the Waste Forecast Analysis [4-3] and supporting memorandum [4-4]. The estimated baseline volume of radioactive waste available to be emplaced in the mound during the first 10 years is 435 000 m^3. Due to current uncertainties in the existing and forecast waste volumes and classifications, the design value of waste volume is 525 000 m^3 for Phase I. The mound is designed to include expansion for up to a total of 1 000 000 m^3 of waste (Phase II).

Based on handling and disposal requirements, the overall NSDF inventory was grouped into six general waste types in [4-3], which are listed in Table 4-1.

Table 4-1 Waste Types and Characteristics (Phases I and II Combined)

Number	Waste Type	% of Total	Physical Waste Characteristics
1	Soil and soil-like waste	37	Environmental remediation wastes - soil, sand, and stone
2	Comingled debris with soil or soil-like waste	8	Environmental remediation wastes, including: • Concrete, wood, rebar, dry wall, shingles, metal, glass, etc. • Soil, sand, and stone. • Trash, including paper, paper towels, plastic, bottles, wood, cardboard, smears, filter papers, rope, nylon, slings, wipes, dry mop heads, personal protective clothing, insulation, air hoses, mop buckets, electric cables, lathe/metal turnings, etc.
3	Non-soil-like waste	<1	Highly organic or highly compressible wastes from Environmental Restoration.
4	Decommissioning and demolition waste	39	Typical materials used in construction, such as: • Metal, aluminum. • Demolition debris, concrete, wood, rebar, dry wall, glass, etc. • Excess equipment and tools. • Soil, sand, and stone. • Trash, including paper, paper towels, plastic, bottles, wood, cardboard, smears, filter papers, rope, nylon, slings, wipes, dry mop heads, personal protective clothing, insulation, air hoses, mop buckets, electric cables, lathe/metal turnings, etc.
5	Packaged waste	15	Waste containerised within a variety of large shipping containers, B-25 containers, drums, buckets and pails, containing: • Metal and aluminum. • Asbestos. • Bituminized waste from water evaporation. • Charcoal, absorbents. • Demolition debris, concrete, wood, rebar, dry wall, shingles, etc. • Excess equipment and tools. • Glass and glassware. • Ion exchange resins (dried or solidified). • Sludges (dried). • Soil, sand and stone. • Trash, including paper, paper towels, plastic, bottles, wood, cardboard, smears, filter papers, rope, nylon, slings, wipes, dry mop heads, personal protective clothing, insulation, air hoses, mop buckets, electric cables, lathe/metal turnings, etc. • Ventilation filters (high efficiency particulate air and roughing).
6	Miscellaneous Waste	<1	Special handling wastes, which do not fit within any of the above categories. Examples include: • Oversized equipment, such as tanks. • Animal droppings/remains that may require sterilization/sanitation.

4.2 Radionuclide Inventory

Chalk River Laboratories has been generating radioactive waste for over 60 years and a significant fraction of the waste currently in storage is planned for transfer to the NSDF. Due to the differences in record keeping methods from present day and 60 years ago, there are some uncertainties in the waste characterization, particularly for some of the older waste streams. Any waste destined for disposal will require further characterization and assessment prior to acceptance at the NSDF.

As part of the PA for the NSDF, an estimate of projected radionuclide inventory was generated, based on data from the Waste Inventory Program, reflecting operational wastes currently in storage at CRL. Characterized inventory of wastes placed in storage between 1995 and 2015, was extrapolated to estimate radionuclide composition of wastes generated prior to 1995 at CRL, as well as those wastes that will be generated and disposed of at the NSDF in the future [4-3].

Concentrations of radionuclides in waste streams that will be generated in the future are expected to be lower by several orders of magnitude [4-5], [4-6], and [4-7], as the majority of wastes that will be generated after 2020 will arise as a result of remediation and decommissioning. Such waste streams will form approximately 85% of the total volume of waste placed within the ECM. Thus, by using radionuclide concentrations in waste streams, which were generated during operations, to represent the total ECM inventory, the total radionuclide inventory within the ECM has been overestimated. This conservatism mitigates uncertainties in the inventory of historic and future waste by ensuring that potential radiological impacts are not underestimated.

The inventory was then screened to remove waste streams which did not meet safety objectives for near-surface disposal and precedence of near-surface disposal at similar facilities elsewhere. The resulting projection was adjusted to remove radionuclides with half-lives of less than five years, because such radionuclides are not of concern for long-term safety. The inventory was also adjusted to account for decay of relatively short-lived radionuclides, such as tritium and cobalt-60, which have reached steady-state as losses due to decay are offset by the current and projected generation rates.

An additional constraint was applied to the total capacity of the NSDF to accept tritium contaminated wastes. Although water in the Perch Creek is not used for drinking, a drinking water limit of 7 000 Bq/L for tritium was applied and the maximum permissible inventory of tritium within the NSDF was calculated to ensure that this value is not exceeded using a set of conservative assumptions and taking into account current tritium loading in Perch Creek of up to 5 000 Bq/L [4-8]. This can be achieved by limiting the quantity of high-tritium waste stored within the ECM that is available for leaching prior to closure (following the end of operations the tritium inventory will be in any case depleted through decay). Tritium inventory available for leaching can be limited by either:

1. Excluding a small number of packages with high tritium content from the NSDF, or
2. Subjecting such consignments to special packaging requirements which are designed to be leak tight and can be credited not to leach during the period of operations.

The activity for the projected NSDF waste inventory is provided in Table 4-2 below for an established list of radionuclides of concern for long-term disposal. The data encompasses bounding inventory for all accumulated and future waste streams which will be ultimately disposed within the ECM. The assumption is that this radionuclide inventory will have been generated by the time the NSDF commences operations in 2020 and is partly present in the form of contamination within facilities which will be decommissioned or within soils which will be remediated. From 2020 until 2070, as the currently stored as well as future decommissioning and environmental remediation waste streams will continue to be placed within the ECM, this radionuclide inventory will be subject to decay and ingrowth.

For the purposes of an accident consequence assessment during operations, it was conservatively assumed that only wastes currently stored within bunkers in WMA B will be involved in the postulated transportation accidents. This is a conservative assumption as the bunker waste packages, on average, has a significantly higher radionuclide content than average for wastes that will be accepted at the NSDF, with a single exception of Ag-108m. The waste inventory considered for the accident consequence assessment and disruptive post-closure scenarios (unless stated otherwise), is summarized in Table 4-3 (see section 7 and 8).

Table 4-2 Reference Radionuclide Inventory at 2020 (Total Inventory) [4-9]

Radionuclide	Half-life (a)	Activity (Bq)	Concentration (Bq/g)[3]	Concentration (Bq/m^3)
Ag-108m	1.3E+02	2.03E+11	9.81E-02	1.47E+05
Am-241	4.3E+02	5.19E+13	2.51E+01	3.76E+07
Am-243	7.4E+03	1.97E+10	9.52E-03	1.43E+04
C-14	5.7E+03	4.41E+13	2.13E+01	3.20E+07
Cl-36	3.0E+05	1.93E+11	9.32E-02	1.40E+05
Co-60	5.3E+00	4.38E+15	2.12E+03	3.17E+09
Cs-135	2.3E+06	6.63E+09	3.20E-03	4.80E+03
Cs-137	3.0E+01	5.31E+17	2.57E+05	3.85E+11
H-3	1.2E+01	4.82E+15	2.33E+03	3.49E+09
I-129	1.6E+07	1.48E+12	7.15E-01	1.07E+06
Mo-93	3.5E+03	3.51E+07	1.70E-05	2.54E+01
Nb-94	2.0E+04	2.97E+13	1.43E+01	2.15E+07
Ni-59	7.5E+04	6.68E+10	3.23E-02	4.84E+04
Ni-63	9.6E+01	2.53E+13	1.22E+01	1.83E+07
Np-237	2.1E+06	3.57E+09	1.72E-03	2.59E+03
Pu-239	2.4E+04	2.01E+12	9.71E-01	1.46E+06
Pu-240	6.5E+03	3.13E+12	1.51E+00	2.27E+06
Pu-241	1.4E+01	1.02E+11	4.93E-02	7.39E+04
Pu-242	3.8E+05	9.37E+09	4.53E-03	6.79E+03
Ra-226	1.6E+03	5.79E+11	2.80E-01	4.20E+05
Se-79	3.8E+00	2.16E+09	1.04E-03	1.57E+03
Sn-126	2.1E+05	3.16E+09	1.53E-03	2.29E+03
Sr-90	2.9E+01	1.66E+15	8.02E+02	1.20E+09
Tc-99	2.1E+05	6.88E+12	3.32E+00	4.99E+06
Th-232	1.40E+10	2.18E+12	1.05E+00	1.58E+06
U-233	7.2E+01	1.88E+10	9.08E-03	1.36E+04
U-234	1.6E+05	3.86E+12	1.86E+00	2.80E+06
U-235	2.5E+05	2.49E+11	1.20E-01	1.80E+05
U-238	7.0E+05	1.24E+13	5.99E+00	8.99E+06
Zr-93	4.5E+09	1.18E+13	5.70E+00	8.55E+06

[3] Concentrations were estimated based on the density of 1 500 kg/m^3, and using a total volume of 1,380,000 m^3 (corresponding to 1,000,000 m^3 of waste mixed with 380,000 m^3 of clean material used during emplacement) [4-9]

Table 4-3 Waste Inventory Considered for Accident Assessment (Bunker Inventory) [4-9]

Radionuclide	Total Baseline Activity (2000 m3) (Bq)	Number of Package [4-10]	Activity per package (Bq) [4-10]	Activity Concentration (2000 m3) (Bq/m^3)	Activity Concentration (Bq/g)
Ag-108m	3.82E+04	8.55E+03	4.47E+00	1.91E+01	1.27E-05
Am-241	3.42E+11	2.20E+04	1.55E+07	1.71E+08	1.14E+02
Am-243	6.28E+07	1.06E+04	5.92E+03	3.14E+04	2.09E-02
C-14	1.07E+11	1.91E+04	5.61E+06	5.35E+07	3.57E+01
Cl-36	3.81E+08	8.53E+03	1.82E-01	1.91E+05	1.27E-01
Co-60	1.53E+15	1.85E+04	2.06E+04	7.65E+11	5.10E+05
Cs-135	3.74E+07	2.29E+04	6.69E+10	1.87E+04	1.25E-02
Cs-137	5.57E+14	1.22E+04	3.06E+03	2.79E+11	1.86E+05
H-3	4.69E+15	2.55E+04	2.18E+10	2.35E+12	1.56E+06
I-129	1.02E+10	2.39E+04	1.97E+11	5.10E+06	3.40E+00
Mo-93	1.11E+05	1.23E+04	8.31E+05	5.55E+01	3.70E-05
Nb-94	1.79E+11	1.06E+04	1.05E+01	8.95E+07	5.97E+01
Ni-59	1.44E+08	2.08E+04	9.66E+06	7.20E+04	4.80E-02
Ni-63	1.10E+11	1.85E+04	7.77E+03	5.50E+07	3.67E+01
Np-237	2.27E+07	1.86E+04	5.92E+06	1.14E+04	7.57E-03
Pu-239	1.03E+10	1.28E+04	1.77E+03	5.15E+06	3.43E+00
Pu-240	1.56E+10	2.08E+04	3.96E+05	7.80E+06	5.20E+00
Pu-241	8.80E+10	2.07E+04	7.53E+05	4.40E+07	2.93E+01
Pu-242	5.55E+07	1.90E+04	4.64E+06	2.78E+04	1.85E-02
Ra-226	3.22E+09	1.17E+04	4.73E+03	1.61E+06	1.07E+00
Se-79	1.00E+07	1.41E+03	2.28E+06	5.00E+03	3.33E-03
Sn-126	8.01E+06	1.22E+04	8.20E+02	4.01E+03	2.67E-03
Sr-90	1.07E+13	1.22E+04	6.56E+02	5.35E+09	3.57E+03
Tc-99	3.72E+09	2.36E+04	4.52E+08	1.86E+06	1.24E+00
Th-232	1.49E+10	2.01E+04	1.85E+05	7.45E+06	4.97E+00
U-233	1.16E+08	7.59+02	1.96E+07	5.80E+04	3.87E-02
U-234	1.57E+10	8.47E+02	1.37E+05	7.85E+06	5.23E+00
U-235	1.05E+09	1.68E+04	9.32E+05	5.25E+05	3.50E-01
U-238	4.31E+10	1.61E+04	6.50E+04	2.16E+07	1.44E+01
Zr-93	4.98E+10	1.78E+04	2.47E+06	2.49E+07	1.66E+01

4.3 Packaging

The majority of environmental remediation and decommissioning waste will be disposed of as bulk material, in unpackaged form. Only about 15% of the NSDF waste will have sufficiently high radionuclide content to require the use of containers. These may include large steel shipping containers (e.g. 20-foot or 40-foot International Organization for Standardization steel box containers, B-25s, drums, buckets, and pails). Shielded concrete caissons/canisters may also be used for items with elevated dose rates, if required.

The waste delivered to the NSDF will not require additional packaging or repackaging. Waste requiring containerization or stabilization shall arrive to the NSDF in containers which meet all WAC conditions for external dose rate and general handling.

Wastes that contain high concentrations of radionuclides must meet stability requirements for the periods of operations and institutional control. This will minimize future radionuclide releases from the ECM. Stable waste packages or waste forms will help limit the releases of radionuclides as components of the disposal system degrade over time. Wastes that contain high quantities of radionuclides such as Sr-90 and Cs-137 must be stabilized for 300 years and wastes that contain high quantities of Tritium must be stabilized for 100 years. This period of time is equal to approximately ten half-lives and allows for significant radioactive decay. Stability can be achieved by using a waste container that is structurally stable and can provide containment for the required period of time or the waste form itself may be conditioned to provide stability, independently of the container. A waste form or container providing structural stability must be capable of withstanding the loads and other conditions in the disposal cell without significant deformation or loss of ability to contain radionuclides. Levels of radioactivity in waste that require stabilization will be determined on the basis of the ALARA principle and to ensure that WWTP can meet CNL's discharge limits (i.e. the Bq/L values shown in Table 7-2).

4.4 Waste Acceptance Criteria

4.4.1 Development

The WAC are being developed in stages, as follows:

- Strategic Waste Acceptance Criteria.
- Interim Waste Acceptance Criteria.
- Preliminary Waste Acceptance Criteria.
- Final Waste Acceptance Criteria.

The Strategic Waste Acceptance Criteria [4-11], and the Interim WAC [4-12] have been developed by CNL. The development of the WAC is an iterative process between the PA, safety analysis and design. Estimated for radionuclides amounts and concentrations are used in the PA to assess the potential dose to the public and risk to the environment. PA results are then used as input into the design and subsequent WAC iterations. The safety analysis requires the radionuclide inventory to assess the safety of the design. The WAC are finalized when the detailed design and safety analysis are both complete.

4.4.2 Radionuclide Specific Restrictions

The NSDF waste acceptance criteria is being developed to ensure that the wastes emplaced in the NSDF are within the bounds of the performance assessment, safety assessment, design basis, regulatory requirements, and are commensurate with the international experience in near surface disposal of radioactive waste.

Specific activity limits were derived to ensure that long-term disposal performance objectives can be met, and provide a sufficient margin of safety. Once established, these limits are used to identify waste streams that can be accepted into the facility. These limits provide a safety envelope for the acceptable inventory, and define radionuclide concentration limits for future administrative controls for waste characterization and acceptance. On this basis, specific activity limits were defined for any waste accepted for disposal at the NSDF for:

- all α emitting radionuclides
- all long-lived β and ϒ emitting radionuclides
- all short-lived β and ϒ emitting radionuclides

Additional restrictions may have to be imposed for waste streams associated with radioactive isotope production and sources, which do not have typical radionuclide distribution.

4.4.3 Hazardous Waste Restrictions

The NSDF will accept radioactive wastes only. Acceptable radioactive wastes will be either non-hazardous, or mixed wastes that are compliant with treatment standards in the Ontario Environmental Protection Act, Regulation 347, General-Waste management [4-13] or demonstrated to be safe for disposal. Restrictions will apply to chemicals which may impact the ECM performance or radionuclide transports, such as chemical complexing or chelating agents.

4.5 Waste Acceptance Protocol

Wastes must meet the requirements of the WAC to be accepted into the NSDF. Wastes consigned to the NSDF will undergo a three tier system of controls consisting of specification, qualification and verification:

- *Specification* – Waste accepted for disposal must comply with the waste form and procedural specification produced by CRL as the disposal site operator. This specification will be developed so that all waste consignments meet the characterization requirements in accordance with CSA N292.0 [4-2] and are controlled in a manner that ensures operational and long-term safety objectives are satisfied.

- *Qualification* – Wastes will have to be produced under approved waste generator QA arrangements, which detail the effective management and control of the waste from its generation to its acceptance by CRL for disposal at the NSDF.
- *Verification monitoring* – In accordance with CSA N292.3 [4-14], CNL will verify that the radioactive waste meets the WAC and can be safely managed and disposed of at the NSDF.

4.6 References

[4-1] International Atomic Energy Agency, *Classification of Radioactive Waste. General Safety Guide* No. GSG-1. 2009.

[4-2] Canadian Standards Association, Ge*neral Principles for the Management of Radioactive Waste and Irradiated Fuel*, CSA N292.0-14.

[4-3] NSDF *Waste Forecast Analysis*, 185-508600-REPT-014, 2016 September.

[4-4] *Expected Waste Volumes for Near Surface Disposal Facility (NSDF),* 232-508120-022-000, Revision 0, April 2016.

[4-5] *Waste Management Areas Source Term*, WMA-508770-REPT-003, Revision 0, 2014 March.

[4-6] *Close-Out of the Building 107 Demolition Project*, B107-508350-PCR-001, Revision 0, 2010 March.

[4-7] *Characterization Summary for the J-Rod Bays in Building 204*, B204-509410-021-000-0008, Revision 0, 2016 January.

[4-8] *Environmental Monitoring in 2015 at Chalk River Laboratories*, CRL-509243-ASR-2015, Revision 0, 2016 June.

[4-9] Kingsbury, R. 2017. Subject: RE: Bunker waste, Email from R. Kingsbury (CNL) to N. Garisto (Arcadis). April 10.

[4-10] CNL. 2017. *Radioactive Waste Radionuclide Inventory used for the Near Surface Disposal Facility Performance Assessment.* 185-508900-TN-003 Rev. 1. March

[4-11] *Strategic Waste Acceptance Criteria for the Near Surface Disposal Facility at Chalk River Laboratories*, 140-508600-WAC-005, Revision 0, 2016 June.

[4-12] *Interim NSDF Waste Acceptance Criteria for the Near Surface Disposal Facility at Chalk River Laboratories*, 232-508600-WAC-002, Revision 0, 2016 December.

[4-13] *Environmental Protection Act, R.R.O 1990*, Regulation 347: General – Waste Management Ontario, 1990.

[4-14] Canadian Standards Association, *Management of Low- and Intermediate-level Radioactive Waste*, CSA N292.3-14.

5. SITE PREPARATION, CONSTRUCTION, AND OPERATIONS

The following sections describe the activities which will take place during the site preparation, construction and operations of the NSDF, as they relate to radiological hazards.

For the purposes of the PA, only activities which have a potential to cause a radiation dose to workers, public or ecological receptors are examined. Potential interactions between project activities on one hand, and radiological impacts on workers, public or ecological receptors are identified.

5.1 Construction Phase (Including Site Preparation)

The NSDF Project will be constructed over two years beginning in 2018. The construction phase begins with site preparation. Site preparation entails mobilizing the site and setting up construction trailers and access control, clearing vegetation, establishing environmental protection measures and earthworks. Once the building site has been prepared, construction of the ECM, WWTP, operational support facilities and site infrastructure will commence.

Before site preparation can begin, an EA decision that authorizes the NSDF Project must be made the CNSC. Similarly, before the construction activities get underway, a licensing decision must be made by the CNSC that amends the CRL Site Licence to include the NSDF as part of the WMAs.

The main components and activities associated with the construction phase of the NSDF Project include the following:

- construction and inactive commissioning of the ECM, including the base liner system and the structural berm;
- development of surface water management structures (i.e., drainage ditches, culverts, ponds);
- construction and inactive commissioning of the WWTP;
- transportation of construction materials to CRL;
- on-site road and access development;
- construction of support facilities (e.g., weigh scale and scale house, laydown and stockpile areas, drum and waste unloading platforms, administration office, staff decontamination facility, vehicle decontamination facility, site vehicle maintenance garage, site and worker parking);
- installation of environmental sampling and monitoring systems;
- installation of security and fencing, and/or connection to existing utilities for the CRL property;
- management of surface water during construction; and
- management of construction wastes.

Radiological hazards during the site preparation and construction phases will be very limited or nonexistent because the NSDF site footprint is substantially undeveloped. There are no significant levels of radiological contamination on the NSDF footprint. However, standard CNL environmental sampling procedures will be followed to establish the baseline radiological characteristics of the site before construction begins. The site preparation and initial construction activities are not expected to release any radioactive effluents to air or water.

5.2 Operations

The operations phase is anticipated to begin in 2020 and end in approximately 2070 (i.e., operating site life of 50 years). The waste streams to be placed in the ECM will primarily originate from operations and decommissioning activities at the CRL property, including legacy radioactive wastes currently stored on site, those from future operations, those which will be generated from the demolition and decommissioning of structures at CRL, and the remediation of some contaminated areas at CRL through to 2070. A small percentage (<5%) of the waste streams to be placed in the ECM will be from non CRL site sources (e.g., CNL's Whiteshell Laboratories, commercial sources such as hospitals and universities).

The main components and activities associated with the operations phase of the NSDF Project include the following:

- phased development of disposal cells;
- on-site transportation (within the NSDF site) of radioactive waste and other wastes that meet the WAC;
- placement of radioactive waste and other wastes that meet the WAC in the ECM;
- progressive closure of disposal cells when filled and installation of cover;
- operation of the WWTP and discharge of treated effluent;
- surface water management and erosion control;
- solid and liquid waste management;
- fuel storage and hazardous materials handling;
- maintenance of the ECM, WWTP operational support facilities and site infrastructure;
- implementation of an Environmental Protection Plan; and
- expansion of CNL's Groundwater Monitoring Program to include the NSDF Project site.

Principal activities, which may be associated with potential radiological exposures of workers, public or ecological receptors are described further.

5.2.1 Staged Development of Disposal Cells

The cell development sequence provides progressive construction, infilling and closure of the individual cells. The placement of waste within the ECM, will be completed in a phased approach:

- Phase 1, with total waste capacity of 525,000 m^3, will accommodate waste now in storage and to be generated for a 20-25 year period beginning 2020.
- Phase 2, with a total waste capacity of 475,000 m^3, will expand the mound to total capacity of 1,000,000 m^3 and allow for wastes generated through 2070.

During the second phase of ECM development, the construction activities will take place in close proximity to the operational activities of placing waste in the open cell of the phase one development and the temporary storage area adjacent to the open cell. As such, workers will need to be protected from potential exposure to gamma radiation and inhalation of gaseous emissions and contaminated dust.

5.2.2 Receiving Waste

Most waste streams to be placed in the ECM will originate from CRL operations, environmental remediation, and decommissioning activities. This includes legacy radioactive wastes currently stored on site. A small percentage (<5%) of the waste streams to be placed in the ECM will be from off-site sources (e.g. Whiteshell Laboratories, commercial non-CNL waste generators such as hospitals and universities). Off-site waste generators will be required to secure the appropriate shipment licenses, in accordance with the regulations and requirements specified in the IAEA Regulations for Safe Transport of Radioactive Material, CNSC's guidance document RP Program Design for the Transport of Nuclear Substances, TDG Act and Regulations, and the Packaging and Transport of Nuclear Substances Regulations under the NSCA [5-1].

All wastes received at the NSDF are required to meet the WAC [5-2]. Compliance of received packages and bulk materials will be verified in accordance with the Waste Acceptance Protocols.

CNL will have a qualified waste acceptance team to review the generator's waste processes, profile and operations in order to approve waste for emplacement into the ECM. All waste will be the responsibility of the generator until it has been accepted by the Waste Operations organization for placement and subsequent disposal in the NSDF.

Activities involving waste receipt will not result in the release of a radioactive effluent to the air or water. The received waste will be a source of external gamma radiation exposure for the NSDF site workers. All receiving activities will comply with the requirements of CNL's RP programs in a manner consistent with the existing waste handling operations in the active WMAs. The principle, As Low As Reasonably Achievable, is considered throughout design and operations, as described in Section 9.2.

A process for what will happen to waste that is not accepted into the NSDF will be developed.

5.2.3 Waste Placement in Temporary Storage Area

Accepted waste may be placed within a temporary storage area within the ECM prior to disposal. Waste may not be in temporary storage (awaiting disposal in the ECM) for more than one year.

Waste will be segregated by waste type (Types 1 through 6 as shown in Table 4-1). Only bulk and packaged contact-handleable waste meeting WAC limits is suitable for temporary storage in the laydown areas. Waste packages containing non-contact-handleable waste as well as waste in high-integrity containers will not be placed in temporary storage, but will be transferred directly for disposal in the ECM.

The maximum quantity of waste that can be temporarily stored within the ECM, pending placement in the open cell, will be limited by physical space available, fire loading, and RP requirements for external exposure.

During temporary storage, it is possible to have minor emissions to air of gaseous radionuclides, such as tritium or C-14, as well as exposure to external gamma radiation and the generation of contact water from precipitation events. The temporary storage area will be prepared and maintained to follow site surface water management plans. Leachate generated at the temporary storage area will be collected and conveyed for treatment at the WWTP.

5.2.4 Waste Handling and Placement into the Engineered Containment Mound

Two methods of waste handling and placement are planned to be used at the ECM, including:

- For waste that cannot be immediately or directly placed in the ECM (typically packaged waste), the shipping vehicle will deliver the waste to the temporary storage area within the ECM. When ready to place the waste in the active cell dedicated equipment is used to carry and position the waste. This equipment is only used in the contaminated areas of the ECM and may include dedicated haul vehicles, cranes, bulldozers, compaction equipment, and other heavy equipment. The design of the temporary storage area includes a drum and waste unloading platform. Compaction equipment may include soil compactors, sheepsfoot rollers, or similar heavy equipment for Type 1, soil and soil-like waste, and Type 3, non-soil-like waste. A landfill compactor (similar to a Caterpillar 826) may be used for compaction of Type 2, comingled radioactive waste, if the waste is highly variable (heterogeneous) or contains significant amounts of refuse or debris waste. Other heavy equipment that may be used for waste placement may include an excavator for bulk waste material and a crane or forklift for placing waste containers, large debris components, and waste packages with high dose rates. Water trucks are used for moisture adjustment and dust control [5-3].
- For waste that can be immediately placed in the open cell (typically bulk waste), the shipping vehicle (e.g. dump trucks, dump trailers) proceeds to the clean dump ramp or other such location within the operating ECM cell. Dedicated equipment (such as a bulldozer) would spread and compact the waste within the cell. This method also minimizes

the potential for contamination of equipment used to transport waste from the generating sites.

The waste haulage vehicles that will deliver the waste from CRL waste locations to the NSDF, are likely to be articulated haulage vehicles, having an approximate 20 m^3 capacity. The trucks transferring waste to the ECM, will range from tandem dump trucks (8 m^3 capacity) to highway semi-dump trailers (20 m^3 capacity).

Haulage vehicles transporting waste to the ECM, will pass through a decontamination facility following unloading, for exterior inspection and decontamination as required, before leaving the NSDF. Equipment that requires decontamination before leaving the NSDF (such as waste haulage vehicles following unloading), will enter the facility, be inspected for loose waste on the exterior box or wheels, and be cleaned using an automated high-pressure, low-volume washing system. Generated wash water will be collected for subsequent transfer to the WWTP for processing.

Other miscellaneous equipment, such as remote telehandlers, may be required to transfer containers or concrete caissons with high-dose rate items.

Dust control will be conducted to support waste placement operations during loading, transportation, placement and compaction operations. Work areas that have the potential for generating dust will require dust suppression techniques and monitoring. Air quality will be monitored for dust that may contain radiological and hazardous constituents to support worker and environmental protection. Waste placement activities may be restricted or suspended if unacceptable amounts of dust are generated.

At the end of each working day, the surface of the waste in the ECM will be temporarily covered with a soil layer (approximately 150 mm thick), tarpaulin, or similar temporary cover system to control the release of fugitive dust from the surface of the waste. Interim cover is removed prior to the resumption of landfilling, to the extent practical.

Temporary storage, waste handling, and placement activities will result in limited emissions to air of gaseous radionuclides, such as tritium or C-14, as well as exposure to external gamma radiation and emissions to water from bulk material placed within active cells during precipitation events. All contact water and leachate generated within the ECM, and waste water generated at the vehicle decontamination facility, will be collected and conveyed for treatment at the WWTP.

5.2.5 Closing and Capping of Full Cells

Once each disposal cell is filled with waste, a cover system, comprised of multiple layers of natural and synthetic materials will be installed to seal the waste, promote run-off of surface water, and to deter water ingress, tree growth and disturbance by animals or future human generations.

The hazards associated with closure activities will be worker exposure due to external gamma radiation and inhalation of gaseous emissions.

5.2.6 Collecting and Treating Leachate

During construction and operation, leachate generated from the ECM, vehicle and personnel decontamination wash water, contaminated runoff, and other liquids requiring treatment will be collected and transferred to the WWTP. Transfer of liquid will be via the active drainage system or by vehicle transfer of drummed liquid waste. The WWTP is expected to operate for the entire operating phase of the NSDF, i.e. 50 years, from 2020-2070 and up to 10 years following closure.

The WWTP has been designed and will be constructed to meet the ongoing treatment requirements for:

- Leachate generated from precipitation that infiltrates the waste placed in the ECM and collected in engineered systems.
- Contact water that is collected from the active waste disposal area.
- Waste water resulting from the decontamination of construction and operating equipment, decontamination.
- Waste water resulting from the use of washroom and personnel decontamination facilities.
- Other contaminated liquids (e.g. from the e WWTP process laboratory).

The WWTP will include several treatment steps, such as filtration and ion exchange (IX) resins. With the exception of tritium, the radioactive contaminants will be removed from the WWTP influent during processing and will meet discharge criteria.

Treated effluent will be sampled prior to its discharge to an exfiltration area at the NSDF site, adjacent to the WWTP. The discharged treated wastewater quality will meet CNL's Acceptability Criteria for Routine and Non-Routine Discharge of Liquids [5-4] on the CRL property, and will be in accordance with CRL's existing licence requirements. Monitoring of the treated effluent will be completed in accordance with CNL's Management and Monitoring of Emissions Procedure [5-5].

Solid secondary wastes generated by the WWTP during operation, will be packaged and placed into the ECM for disposal. Liquid wastes generated by the WWTP process itself will be recirculated and treated.

In addition to discharge of treated water to an infiltration area, WWTP operations may result in small emissions of radioactivity to air via the active exhaust air system. Releases to air will be minimized by a pre-filter bank and a High Efficiency Particulate Air (HEPA) filter bank. These operations may also cause external radiation exposure to NSDF personnel and mitigation measures are included in the NSDF design and facility operating procedures.

5.3 Potential Impacts and Interactions

Table 5-1 summarizes the predicted interactions between various NSDF operations and potential dose to workers, public and non-human biota, as required for the purposes of the EIS.

Table 5-1 Interactions Between NSDF Operations and Doses to Workers, Public and Non-Human Biota

Operation/Activity	Dose to workers	Dose to public	Dose to non-human biota
Site Preparation and Construction	No	No	No
Receiving waste	Yes	No	No
Waste placement in temporary storage area	Yes	No	No
Waste handling and placement in the ECM	Yes	Yes	Yes
Closing and capping of cell	Yes	Yes	Yes
Collecting and treating leachate and other contaminated water	Yes	No	No

5.4 References

[5-1] *Packaging and Transport of Nuclear Substances Regulations*, CNSC, SOR/2015-145, 2015.

[5-2] Interim NSDF Waste *Acceptance Criteria for the Near Surface Disposal Facility at Chalk River Laboratories*, 232-508600-WAC-002, Revision 0, 2016 December.

[5-3] *Waste Placement and Compaction Plan*, B1550-508600-PLA-001, Deliverable 14.1, Revision 0, 31 March 2017

[5-4] Acceptability Criteria for Routine and Non-Routine Discharge of Liquids on the CRL Site, CRL-509200-PRO-638, Revision 2, 2016 June.

[5-5] Management and Monitoring of Emissions. CW-509200-PRO-001, Revision 0. 2013 May 30.

6. PRINCIPAL FACILITY DESIGN FEATURES CONSIDERED IN THIS ASSESSMENT

This section includes the principal facility design features [6-1].

At the time of this assessment, the NSDF is at the 100% design stage and it is likely that there will be few refinements to the concepts described below. Such changes, however, will be within the overall safety envelope of the bounding analysis presented within this PA.

6.1 Overview

The general site layout is provided in Figure 6-1. The NSDF will include an ECM with a disposal capacity of 1 million m^3 of waste. An engineered base liner and final cover will contain the waste and isolate it from the surrounding environment. Both the liner and cover will consist of several layers of natural and synthetic materials that, when combined into a composite barrier system, will provide the required engineering properties and service life of 550 years.

Infiltrated rainwater may come into contact with waste within the ECM prior to sealing of the disposal cells. This will result in generation of contaminated leachate. The leachate collection and monitoring system design will prevent release of contaminated leachate to the environment. Collected leachate will be transferred for processing at the WWTP, where radionuclides and other contaminants will be removed prior to release of the treated water.

Several other infrastructure and support facilities necessary to operate the NSDF will be constructed. These will include (Figure 6-1):

- Access Gates and Security Guard Building.
- Haul Roads and Cell Access Roads.
- Administration Building.
- Temporary Storage and Waste Receiving and Processing Areas.
- Laydown and Stockpile Areas for Equipment and Vehicles.
- Vehicle Decontamination Facility.
- Weigh Scales and Waste Acceptance Control.
- Unloading Platforms and Access Ramps.
- Stormwater management ponds.
- Wastewater Treatment Plant (WWTP).

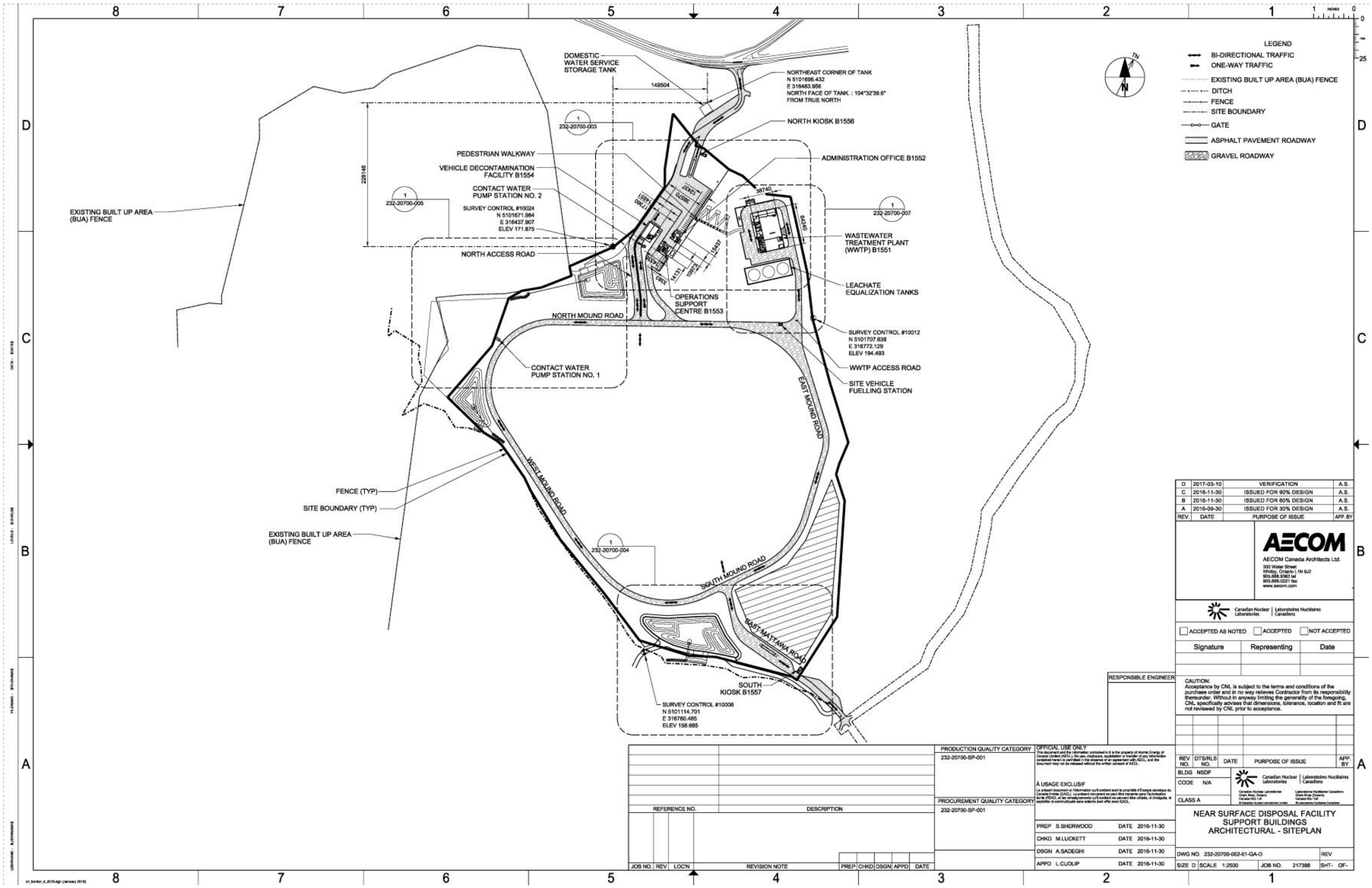

Figure 6-1 Near Surface Disposal Facility Layout

6.2 Engineered Containment Mound

The NSDF ECM (Figure 6-1), will include a base liner and final cover design (Figure 6-2), leachate collection system, and a passive gas venting system.

The final cover system is designed to protect both the human and natural environment from the contained wastes. The final cover system will be sloped to promote surface water runoff and to mitigate infiltration into the cap, thereby, reducing leachate generation. The cover will include a minimum top plateau slope and a maximum side slope grade to ensure positive drainage off the ECM final cover system.

The Slope Stability Analysis (SSA) [6-2] provides the information needed to support the design of the base slopes, sidewalls, and side slopes of the ECM. The SSA addresses the range of anticipated loading conditions, under both short-term and long-term scenarios, to confirm that the slope designs satisfies the minimum factor-of-safety requirements for stability. The SSA also includes the analysis and specifications used to determine the maximum slope for the placement of each waste stream, as applicable.

This will minimize erosion and undesirable component stresses. The final cover system is designed to support low vegetation (i.e. grasses), to mitigate erosion and sedimentation of the cap materials.

The composite base liner and final cover system design fully encapsulate wastes within the ECM and isolate them from the groundwater. Due to the expectation of organic waste being disposed inside the ECM, a gas collection and venting design is included. This design ensures that any landfill gas pressure buildup will be relieved. It is assumed that these vents will be plugged in the post-closure period, following the cessation of gas generation, in order to ensure the long-term integrity of the ECM cap [6-3].

The bottom of the base liner will be maintained at least 1.5 m above groundwater at all times. The primary liner system will include the leachate collection system, and the secondary liner system will contain the leak detection system. The secondary liner will protect the environment in the unlikely event that the primary liner system fails.

The ECM design will provide the following additional design features:

- Erosion protection to ensure that the rate of erosion due to action of surface water and wind is minimized.
- Subsidence protection so that the cover and geomembrane components can withstand settlement in the foundation soils.
- Structural stability, specifically designed for a seismic event.
- Bio- and human intrusion barriers. A marker system will be used to warn future generations of the dangers of the disposed waste. During operation, a fence will be placed around the site to prevent animals and unauthorized personnel from entering the site.
- The bottom liners will be placed below the annual freeze-thaw cycle.

The ECM dimensions that are relevant to the PA, are listed in Table 6-1.

Table 6-1 Engineered Containment Mound Dimensions

Parameter	Dimension
Internal footprint	99,750 m^2 [6-4]
Average thickness of waste layer	13.83 m [6-4]

The final cover and liner systems are described in the following sections.

6.2.1 Final Cover

The multi-component final cover system will be constructed over the entire surface of the completed containment mound. to seal the emplaced wastes from the environment and provide shielding for the 550-year design life of the ECM. The final cover system will include the following layers, listed from top to bottom (see Figure 6-2):

- 0.15 m thick Top Soil to provides a growth zone for hardy grasses.
- 0.6 – 1.2 m thick Sandy Loam to provide moisture retention for plant uptake and evapotranspiration.
- 0.2 m thick Granular ‘A’ clear drainage layer to provide a natural filter layer to minimize the possibility of fines migrating downward from the sandy loam fill layer to the underlying intrusion biobarrier to help minimize the potential for future clogging of the biobarrier layer.
- 0.5 m thick Intrusion Barrier Rockfill to deter burrowing animals and roots from potential deeper-rooted plant species reaching and possibly damaging the cover lining system, as well as penetrating into and transporting contaminants from the waste fill. This rockfill layer would also help deter inadvertent future intrusion into the buried wastes by humans. The layer will also provide for some lateral drainage of water that percolates through the upper layers of the cover.
- 0.3 m thick Granular ‘A’ protection layer will provide, in conjunction with the underlying HDPE geomembrane, a means for conveying lateral drainage within the cover of water that percolates through the upper layers of the final cover. Granular ‘A’ rock is generally composed of high-stability graded sand and gravel.
- 80-mil Textured High-Density Polyethylene (HDPE) Geomembrane which serve as the upper (primary) barrier against infiltration through the cover into the buried wastes. It is also expected to prevent or minimize the upward migration of radon and other landfill gases from the waste fill into the atmosphere.
- Geosynthetic Clay Liner (GCL) which functions as a lower (secondary) low permeability barrier that also limits the downward leakage through any potential defects that might exist in the overlying geomembrane liner and provides a back-up hydraulic barrier in the

unexpected event that the geomembrane experiences deterioration over the design life of the facility.

- Landfill Gas Venting (Sand Interim Cover) Layer – 0.3 m which is placed directly above the waste material. It also provides a layer to promote lateral venting of landfill gas beneath the HDPE geomembrane/GCL barrier component in the final cover.

The cover system components are expected to meet the 550-year-long design life, by averting excess settlement, ponding, and excessive cracking. Additional description of each component is provided below [6-1].

6.2.2 Base Liner and Leak Detection System

This lining system consists of redundant primary and secondary liner systems, with each component system containing both natural and synthetic barriers (see Figure 6-2).

- The secondary liner includes a 0.75 m thick compacted clay liner, followed by a HDPE geomembrane liner, a non-woven geotextile layer, and secondary granular drainage/collection layer.
- The primary liner system is located above the secondary liner, and consists of a GCL, a HDPE membrane liner, a geotextile cushion, a 0.5 m thick granular leachate collection system (LCS) drainage layer, and an overlying 0.3 m thick granular filter layer.

The basal liner is designed for the top of the primary liner system to remain at least 1.5 m above the maximum anticipated seasonally high groundwater elevation. Both the primary and secondary liner systems have a hydraulic conductivity of $1.0x10^{-7}$ cm/s or less.

A leak detection system (LDS) is a part of the composite base liner system. The leak detection system in the base liner is designed to monitor the integrity of the engineered barriers and is the secondary containment system for any leachate that may be released through the primary liner. The LDS separates the primary and secondary composite liners and consists of a sand protection layer, a 9.5 mm dimeter clear stone drainage layer on the floor of each cell and an LDS leachate collection system within each of the five internal collection/pumping sumps at the south end of the lined ECM containment area.

6.3 Waste Water Treatment Plant

The wastewater treatment plant (WWTP, Figure 6-3) includes a dual train (Train 1 and Train 2) treatment system for treating NSDF effluent, including contact stormwater and leachate from the ECM, equipment and personnel decontamination water, and laboratory wastewater. Peak leachate generation is expected during the last stages of operation, when the mound is at its greatest surface area, but before the final cap is installed over the last active cell. Leachate generation is expected to cease a few years after the ECM is closed and capped. Leachate generation will continue to be monitored and contaminated leachate will continue to be treated at the WWTP for as long as it is generated, after which time the WWTP will be dismantled as it will be no longer needed.

6.3.1 Influent Equalization

The influent equalization system is designed to store and equalize wastewater produced at the NSDF, including:

- ECM leachate.
- ECM contact stormwater.
- Equipment and personnel decontamination water.
- Laboratory wastewater.
- Recycle flows from the WWTP.

The wastewater volumes were developed for the purpose of determining the long-term average wastewater volumes that are used to establish the flow-rate design capacity of the WWTP. Extreme precipitation events were not considered, as their effects are mitigated by the temporary storage capacity provided by the three equalization tanks [6-5]. Each equalization tank has a capacity of 1,900 m^3, which are sized to contain two back-to-back 100 year, 24 hour storm events (2,820 m^3). The WWTP will be operated to ensure that the volume of leachate contained within the tanks is kept to a minimum and, in the event of a spill, can be accommodated within a concrete secondary containment. The freeze-protected equalization tanks will be equipped with insertion-style heaters to maintain wastewater temperature above freezing, and will be insulated and cladded to minimize loss of heat. From these tanks, collected leachate will be transferred for treatment at the WWTP, which will be a temperature-controlled building for year-round operation. Three pumps (two duty, one standby), equipped with variable frequency drives, will be installed within the WWTP building and will transfer wastewater from the influent equalization tanks to Train 1 and/or Train 2 of the treatment system. An overview of principal treatment stages is provided below.

6.3.2 Chemical Precipitation

Each treatment train will include two chemical precipitation tanks operated in series (four tanks in total). Chemical precipitation is designed for significant removal of heavy metals and the radionuclide surrogates for strontium and cobalt. In addition, chemical precipitation achieved significant removal of cations such as iron, calcium, and magnesium, which can negatively impact downstream treatment processes used for polishing treatment and removal of additional radionuclides. The chemical precipitation tanks have been sized to provide a minimum of twenty minutes of hydraulic retention time at the design flow rate of 11,360 litres per hour.

6.3.3 Membrane Filtration

Membrane filtration will provide nearly complete removal of suspended solids from the chemically pretreated wastewater. Membrane filtration provides a barrier through which suspended solids cannot pass, effectively eliminating the presence of suspended solids in the filtered effluent. Suspended solids concentrations in membrane filter permeate are expected to be less than 5 mg/L. The membrane filtration system includes feed and process tanks on the inlet side, and associated pumping equipment for transferring wastewater through the membrane filtration unit.

A dedicated clean-in-place system will serve each membrane filtration system to provide chemical mixing and recirculation of cleaning chemicals through the membrane filters on a periodic basis. Typical cleaning frequency for this type of wastewater is approximately once per week. Based on the ongoing pilot scale test, sulfuric acid was demonstrated to be effective for cleaning of the membranes. Low volumes of additional cleaning chemicals, including sodium hypochlorite for control of biological fouling, and sodium hydroxide for removal of organic material, are also expected to be required for long-term maintenance of membrane flux rates. After cleaning, the spent cleaning solution may be recycled for use during subsequent cleaning cycles, or will be discharged to the equalization tanks for re-processing through the WWTP.

6.3.4 Permeate pH Adjustment

The pH of permeate from the membrane filtration process is expected to be elevated, and may need to be reduced prior to subsequent polishing treatment processes. Each treatment train will include a pH adjustment tank and feed tank for the downstream processes.

Filtered wastewater will be transferred by gravity from the pH adjustment tanks to the polishing process feed tanks

6.3.5 Granular Activated Carbon

Two granular activated carbon (GAC) vessels will be operated in a lead-lag fashion to provide removal of organic chemicals that may be present in the NSDF wastewater. Each GAC vessel will be constructed of coated carbon steel, and will contain 900 kilograms (2,000 pounds) of GAC for adsorption of the Contaminant of Potential Concern (COPC). When the GAC in the lead vessel reaches its capacity to adsorb the COPC, the GAC will be replaced with fresh media, or the entire GAC vessel will be exchanged for a new vessel containing fresh media. The vessel with fresh GAC will be placed in the lag position, and the former lag vessel will be placed in the lead position.

6.3.6 Ion Exchange

Ion exchange technology will provide polishing treatment for removal of low concentrations of metals and radionuclides that remain after chemical precipitation. Each ion exchange treatment train will include a total of 6 ion exchange vessels in a lead-lag arrangement to remove the range of constituents expected to be present in the NSDF wastewater. Each ion exchange vessel will contain resin specific to the Contaminant of Potential Concern to be removed from the wastewater. The design includes two vessels in a lead-lag arrangement for each of the following resins:

- Zeolite (cesium).
- Strong acid cation (heavy metals and cationic radionuclides).
- Anion (anions and anionic radionuclides), if needed.

6.3.7 Final pH Adjustment

The effluent pH will be adjusted to meet the effluent discharge pH requirement of 6 to 9 standard units. Effluent from the ion exchange vessels will be conveyed by residual pressure to the final pH adjustment tanks. The final pH adjustment tanks are sized and equipped in an identical manner to the initial ion exchange pH adjustment tanks, and will be used to control the pH of the final effluent to within an acceptable range for discharge.

6.3.8 Final Effluent Storage

Treated effluent from the final pH adjustment tanks will be conveyed by gravity to the final effluent storage tanks, each sized for eight hours of hydraulic detention time at the design flow rate of 11.36 m^3/hour (50 gpm). The final effluent storage tanks provide storage of final effluent for sampling prior to discharge.

6.3.9 Residuals Management

It is estimated that an average of approximately 1 to 2 m^3/day of residuals will be produced from the chemical precipitation and membrane filtration process with a solids concentration ranging from 15,000 to 50,000 mg/L. The estimated mass of residuals is 20 dry kilograms per day (20 kg_{dw}/d. Residuals will be dewatered and conditioned by chemicals, if needed. The filter press dewatering operation is a batch process, consisting of filling the press with residuals for dewatering, building pressure to complete the dewatering process, and opening the press to allow dewatered residuals to be removed. The filter press will be equipped with a diatomaceous earth pre-coat system to enhance residuals dewaterability, if needed.

Two pumps (one duty pump for each train) transfer residuals from the membrane filtration system process tanks to the residuals storage and conditioning tanks.

Each tank will be closed top, vertical cylindrical with cone bottom, and constructed of stainless steel or fiberglass with a capacity of approximately 80 m3. Each tank will be equipped with a mixer, level instrument, and decant ports. The mixers will be used to blend conditioning chemicals with the residuals, if needed, to enhance dewaterability.

Based upon the projected wastewater quantity and characteristics, and results of laboratory and pilot scale tests, the annual quantity of dewatered residuals is expected to be approximately 13 m^3/year, and the annual quantity of spent GAC and ion exchange resin is expected to be approximately 17.5 and 22 m^3/year, respectively. The level of radionuclides in the dewatered residuals and spent GAC and ion exchange resin is expected to be acceptable for disposal in the ECM without containment or packaging.

Once the ECM is closed, the volume of water for treatment will reduce to a substantially smaller flow, as will the quantity of residual solids, which will be disposed of elsewhere.

6.3.10 Safety Design Features

The WWTP and leachate management system design will provide the following design features:

- Sufficient storage capacity will handle any buildup of leachate in the event of a prolonged WWTP outage.
- Appropriate structures and systems have been designed to withstand high wind events.
- Provision of standby Class III power via on-site generators, to ensure safe operation of the leachate management system in the event off-site power fails.
- The WWTP will treat leachate and wastewater such that the released effluent will meet CRL Acceptability Criteria for Routine and Non-Routine Discharge of Liquids to Stormwater for all parameters, except tritium.
- Sufficient sump capacity and secondary containment will be provided to handle potential spills of radioactive and hazardous liquids.
- Heating will be provided to ensure that pipes and tanks can safely operate during cold periods.

6.4 Infrastructure and Support Facilities

The following infrastructure will be required to facilitate the NSDF construction, operation and maintenance:

1. Main site access road.
2. Perimeter access and maintenance road.
3. Perimeter fencing.

The NSDF will also include the support facilities described earlier.

The following utilities will be required for NSDF construction and operation:

4. Potable water service for human consumption, WWTP operations, staff, and vehicle decontamination facilities.
5. Electricity for site facilities for lighting, heating, venting, and air conditioning; and other power uses.
6. Telephone and internet access for communication and CNL surveillance equipment (such as security cameras).
7. Sanitary and grey water systems to treat water from washrooms, as well as staff and vehicle decontamination facilities.

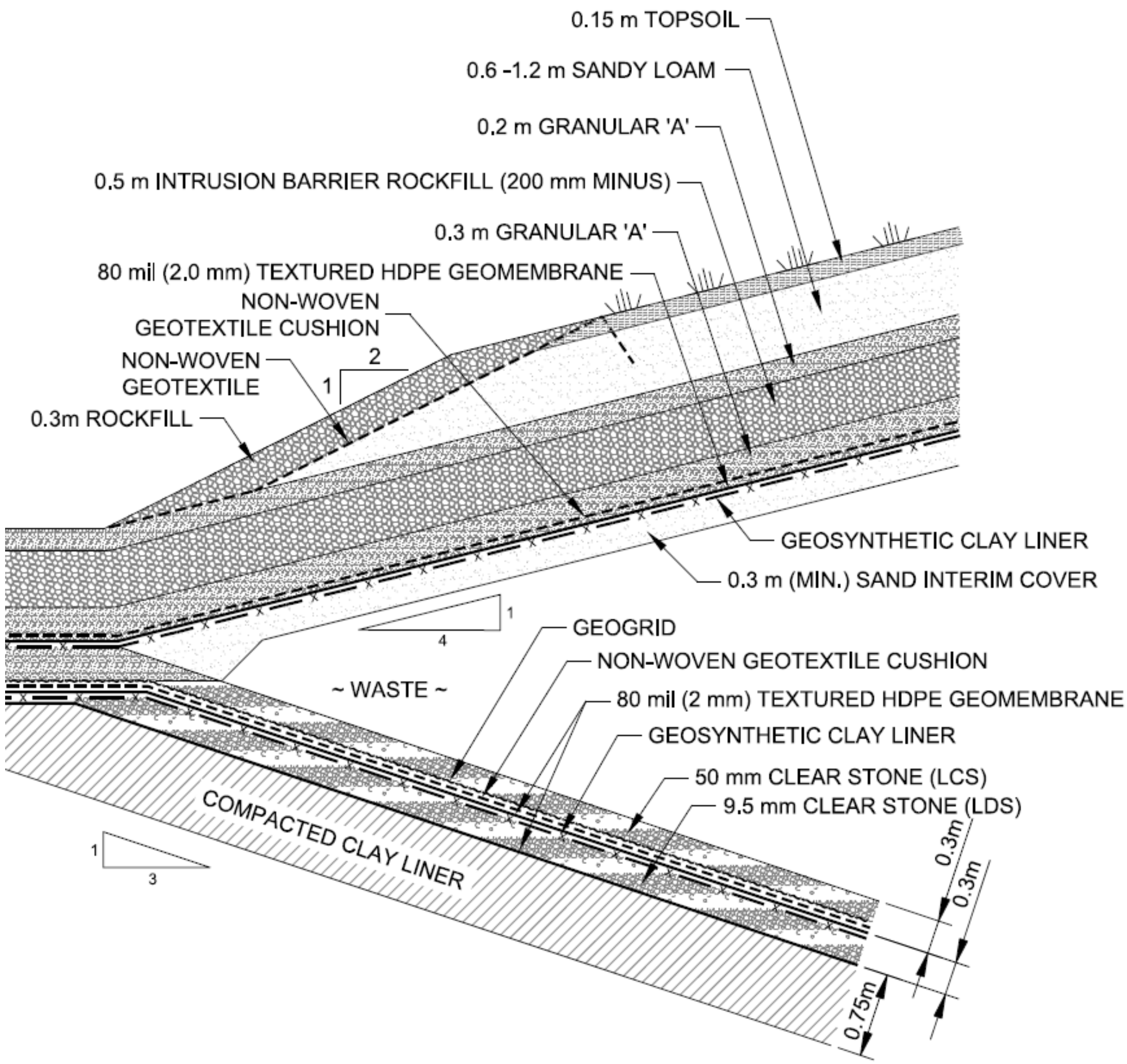

Figure 6-2 Final Cover and Base Liner System

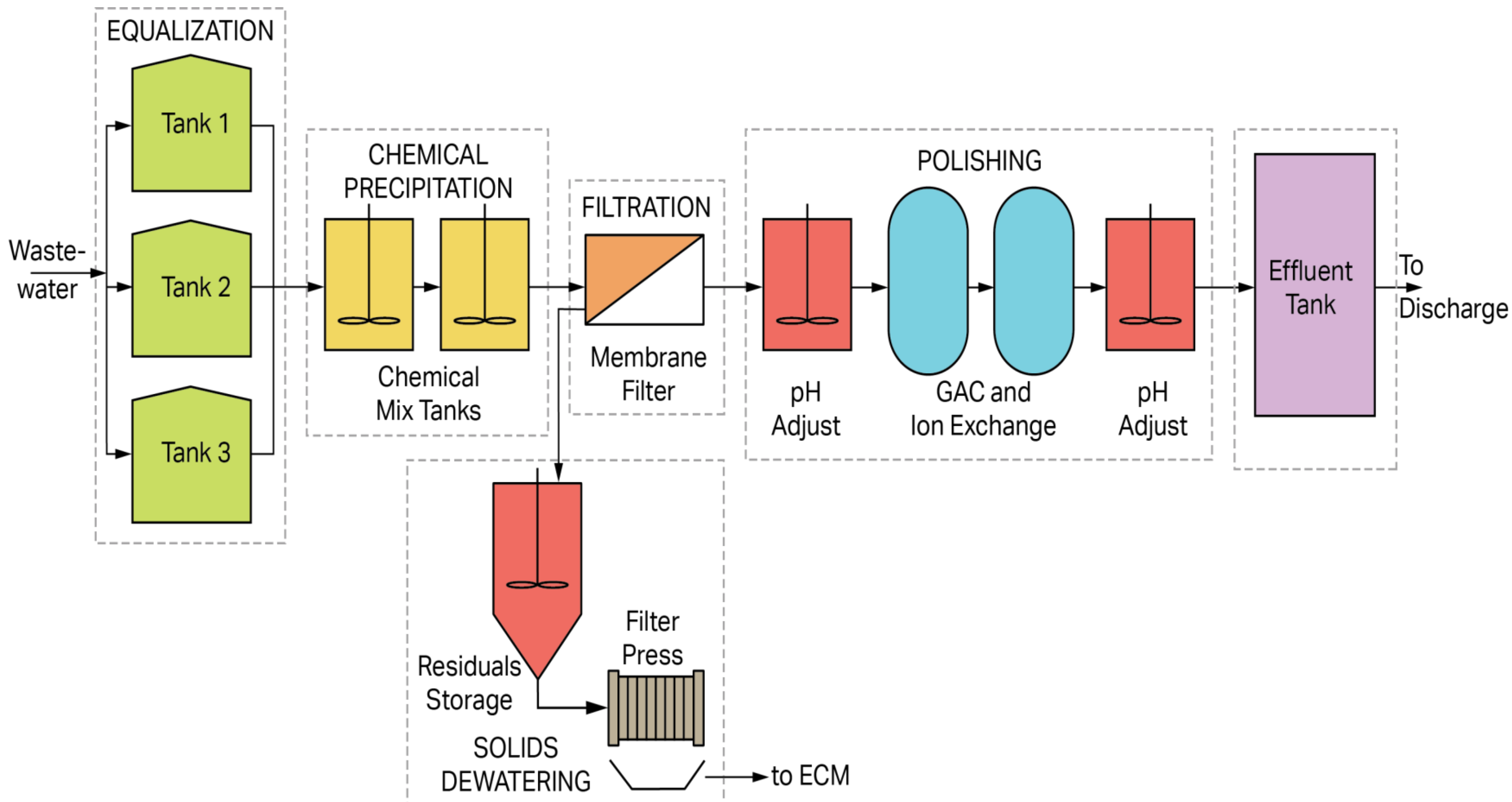

Figure 6-3 Waste Water Treatment. Process Flow Diagram

6.5 References

[6-1] *Design Description*, 232-503212-REPT-003, Revision C, 2017 January.

[6-2] AECOM. 2016. *Slope Stability Analysis* (TSW 232-503212-TSW-001, Revision 3, Table 9, Deliverable 1.12), Revision 0, 60% Design.

[6-3] *Landfill Gas Management Plan*, Deliverable 4.3, Revision B, NSDF-508600-PLA-003, 2016 November.

[6-4] Kingsbury, R. 2017. Subject: RE: Bunker waste, Email from R. Kingsbury (CNL) to N. Garisto (Arcadis). April 10.

[6-5] CNL, *Leachate and Wastewater Characterization (Quantity and Quality),* B1551-508600-REPT-001, Revision 0, 24 February 2017.

7. PRE-CLOSURE SAFETY ASSESSMENT

Pre-closure assessment covers the period of the NSDF operations until closure in year 2070. Radiological safety of workers during normal operations will be assured on the basis of the current RP program as applied in WMA for handling radioactive waste. The NSDF will operate under the site licence and governance and will handle similar waste streams to WMA facilities.

All radiological effluents will be treated and monitored prior to release into the environment. Radiological impacts on members of the public and non-human biota resulting from such emissions are evaluated using models, consistent with the CSA N288.1-14 [7-1] and N288.6-12 [7-2].

Abnormal events and accident scenarios are defined using a hazard identification and screening process which is documented in Section 7.4.2. From the resulting range of plausible scenarios, bounding accident scenarios are selected, involving maximum quantities of radioactive material, to evaluate feasibility of operating the NSDF in compliance with safety criteria for accidents (see Section 2). Consequence assessments are carried out for such bounding scenarios.

Subsequently, ALARA planning, worker dose assessment for normal operations and a systematic set of hazard analyses and consequence assessments have been developed in support of detailed and final designs and are presented in the SAR, but this is outside the scope of this report.

A pre-closure process flow diagram, illustrating this process is presented in Figure 7-1. The figure shows key assessment steps and how they interact with the other project aspects, such as EA, design, site characterization, and definition of the WAC.

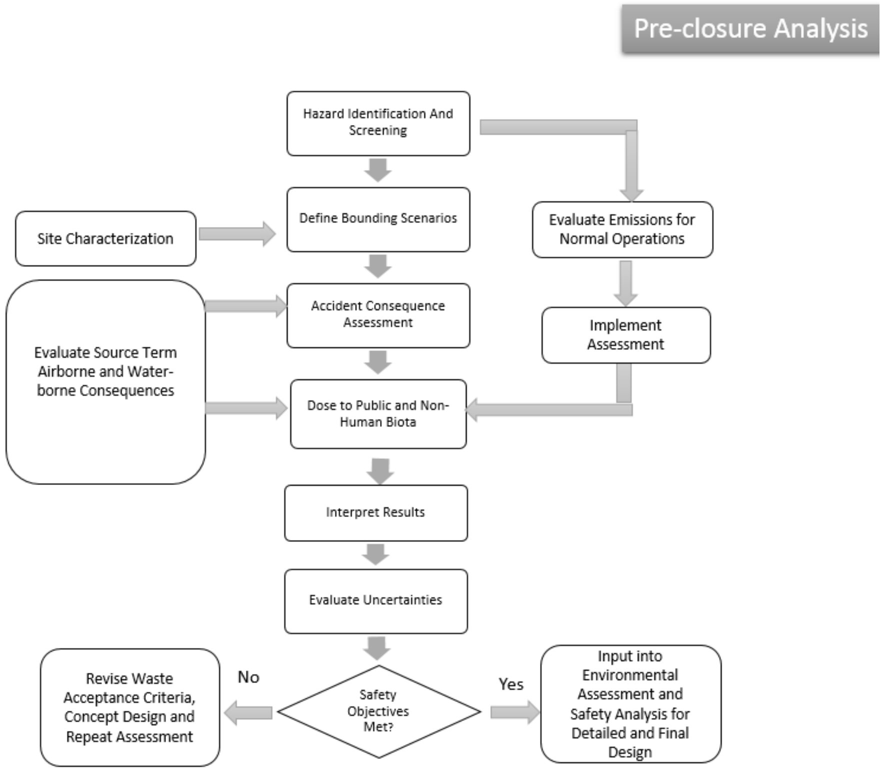

Figure 7-1 Process Flow Diagram for Pre-Closure Analysis

7.1 Radiological Safety During Normal Operations

7.1.1 In-Design Mitigation

Radiological effects on workers will be minimized using mitigation measures which have been developed during the design of the NSDF and its associated infrastructure (e.g. the WWTP). These in-design mitigation measures will include the following features:

- **Shielding**: This may include appropriate design of waste container or shielded flasks and caissons, appropriate design of the ECM emplacement cells, provision of day-cover over the waste within uncovered cells, and the WWTP control room.
- **Provision of remote handling capability for non-contact handleable packages**: This may include provision of telehandlers, cranes or similar equipment which permits workers to undertake operations at a safe distance from radioactive waste packages.
- **Ventilation**: Active ventilation will be provided for enclosed spaces, e.g. within WWTP. This will prevent build-up of radioactive gases.
- **Leachate minimization and treatment**: Sump and stormwater collection and management will be used to prevent uncontrolled releases of radioactive effluents.
- **Emission control (airborne and waterborne):** All effluents will be monitored prior to release. Only decontaminated wastewater with acceptable concentrations will be released.

- **Zoning and Monitoring**: This will be used to prevent spread of particulate and water-borne contamination.

These in-design mitigation measures and radiation safety governance are taken into account in the following assessment, and are described in greater detail in the design documentation.

7.1.2 Doses to Nuclear Energy Workers

Facility workers may have increased risk to exposure via the following pathways:

- External Radiation Dose
- The NSDF design ensures that workers can implement their functions without exceeding CNL's occupational dose target.
- Inhalation and Immersion Dose
- Air concentrations of tritium, carbon-14 and radon in the NSDF are estimated below. The NSDF facilities are designed to ensure that air concentrations of gaseous isotopes are below the Derived Air Concentration for workers. Inhalation and immersion doses to workers are expected to be below CNL's occupational dose target.
- Contamination
- Workers may be exposed to external or internal irradiation due to coming into contact with contaminated materials or ingesting/inhaling airborne contamination. Canadian Nuclear Laboratories has, and will be applying a rigorous contamination control system, which is described in Section 9.

Bounding estimates of external exposure to operating staff handling radioactive waste at the NSDF can be made assuming the duration of operations are consistent with the current waste handling at CRL's Modular Above Ground Storage Facility [7-3]. Although the processing rate will be higher, the vast majority of waste streams that will be handled at the NSDF will contain lower inventories of radioactive materials. Ultimately worker exposure is driven by CNL's RP management program, which will be consistent with the current operations.

The following is a list of the relevant operational activities identified in the NSDF Waste Placement Plan [7-4] (see Section 5 for details on operation):

- Waste inspection (radiation monitoring) to verify compliance with the criteria set out in the NSDF WAC.
- Waste transfer to disposal cell for placement.
- Waste placement into the disposal cell.

Upon receiving the waste package at the NSDF, the Contamination Monitor (CM) staff and the Radiation Surveyor (RS) staff may inspect the waste package and conduct radiation monitoring to ensure the package meets the WAC. Similar inspections may be performed for vehicles transferring unpackaged bulk waste, such as contaminated soil and decommissioning debris. Section 5 discusses this in further detail.

It is assumed that handling and on-site transfer to the designated disposal location for high dose-rate consignments may be conducted using telehandlers or similar equipment. Shielded concrete caissons may also be used to ensure that dose rates meet the NSDF WAC and that doses to personnel are below regulatory limits and ALARA.

The NSDF operations will receive and handle one waste consignment at a time. The filling sequence will begin with the initial operational lifts. To prevent personnel and equipment from exposure or contact with contaminated materials, separation techniques will be used (e.g. operational cover, fixatives, platforms, or plastic tarping). The operational cover (daily/interim cover) will consist of clean soil stockpiled on site as it becomes available from the excavation for the NSDF base or other suitable borrowed sources. Once placed within the appropriate cell location, waste may be compacted using appropriate equipment, such as wheel tractor soil compactor or large bulldozer.

The SAR provides evaluation of operational doses to workers based on operational procedures which were available when SAR was prepared [7-5].

Canadian Nuclear Laboratories RP program, will ensure doses to workers are below limits and ALARA. Furthermore, operations at the NSDF will be similar to those applied by CRL to operation at WMAs, incorporating lessons learned for the past 60 years. This is indicative of the safe operating procedures followed in the facility operations.

A brief summary of the operating experience gained over the years from the WMA operations is described below. The information presented in these sections is based on the data from the WMA Annual Safety Reviews [7-6], [7-7], [7-8], [7-9], [7-10], [7-11], [7-12], [7-13], [7-14], [7-15], [7-16], [7-17], [7-18], [7-19], [7-20], [7-21], [7-22], [7-23], and [7-24].

There were no exposures above individually assigned Dose Control Points, nor were there exposures at or above established internal Action Levels (AL). In general, the average doses have been much less than half the current regulatory limits and there have been no individual doses in excess of the current regulatory limits (i.e. 50 mSv/year).

Employees are monitored for internal contamination through a routine bioassay program, which involves both direct measurements with radiation detectors (whole-body counting) and indirect bioassay monitoring (radiochemical analysis of excreta samples).

Detailed dose ALARA planning will be developed in parallel with the detailed design for the NSDF to ensure that worker doses are minimized. However, all operations will be subject to the same RP program that is currently used at CRL and which is described in Section 9.

7.2 Radiological Assessment of Doses to Public

7.2.1 Methodology

Site preparation and construction and operations phases of the project could involve the release of radioactive materials to the environment prior to closure of the NSDF; such as releases to atmosphere, e.g. due to emissions of gaseous radionuclides disposed within the ECM. Waterborne releases into the environment will involve treated effluent following processing at the WWTP. Consequently, this could result in the potential contamination of various media, including air, surface water, soil, sediment, groundwater, and other media such as vegetation. The methodology used to estimate doses to members of the public from routine emissions of radioactivity, considered exposure pathways and analytical parameters that are consistent with the CSA N288.1-14 [7-1].

The analysis was conducted using RESRAD and IMPACT codes (see Section 1.9) and involved the following steps:

1. Source term assessment – evaluation of radiological emissions to air and water.
2. Selection of PCG for airborne and waterborne pathways.
3. Modelling of radionuclide transport in air and groundwater.
4. Modelling of radionuclide transfer in the biosphere and dose assessment.

7.2.2 Key Assumptions for Public Dose Calculation

Doses to members of the public during pre-closure were calculated based on the following parameters and assumptions:

- The effluent from the WWTP will be discharged to the infiltration area and will ultimately discharge into the East Swamp Stream. No credit is taken for dilution prior to contaminants entering the East Swamp Stream, which is a conservative approach.
- This effluent will contain radionuclides at maximum permissible levels, as described further in Section 7.2.4. This is a conservative assumption because most of the effluent will contain levels of radioactivity below limits.
- Human habits, including local food and water consumption, are unchanged from the current conditions, as defined by the site-specific Lifestyle Survey [7-25].
- At the beginning of the waste placement (2020), the total annual volume of water expected to require treatment will be about 9,916 m^3. This includes 1,848 m^3 of leachate from the active cell, 2,808 m3 of contact water from the active cell, 5,160 m^3 from the temporary storage pad, and 100 m3 of decontamination water. When Cell 1 is filled, the final cover will be placed over Cell 1 and the leachate volume will decrease from 1,848 m^3/yr to 12 m^3/yr. At the same time, Cell 2 will be operational and begin generating both leachate and contact water [7-26].
- The maximum effluent *from the WWTP* is generated at the rate of 10,024 m^3/y in 2070 [7-26].
- The flow rate in the East Swamp stream (shown as ESW in Figure 3-3) is 197.3 m^3/d or 7.2E4 m^3/y [7-24].
- The flow rate in the Perch Creek (shown as PCW in Figure 3-3) is 1.77E6 m^3/y [7-24].
- Future climate, hydrological and hydrogeological conditions, *within the pre-closure period*, are assumed to be the same as current conditions.

Hypothetically, members of PCGs could be exposed to external gamma radiation from the waste. However, the gamma dose rate at the NSDF fence line will be below 10 µGy/h, which is the limiting criterion. External exposure will be reduced to negligible levels at all locations where PCGs reside. Therefore, the impact of direct gamma radiation on human health is not considered further.

7.2.3 Radiological Emissions to Air

Discharges to air could occur during operations of the ECM. This may involve the emissions of radioactive dust during handling of bulk materials and emissions of gases during temporary storage and disposal of radioactive materials. Minor radiological emissions due to dust dispersion will be minimized by using daily cover and other dust abatement and control features. However, gaseous radionuclides will be released to the atmosphere during normal operations, notably:

- Tritium in the form of HTO and
- Various gases containing C-14.

In addition, radon (Rn-222) will also be released from the ECM due to the decay of Ra-226, Pu-242, U-234, and U-238.

Releases from the ECM will dominate minor fugitive emissions of radionuclides resulting from the operation of the WWTP, which will be further mitigated by the use of High-Efficiency Particulate Air filters and scrubbers, as required.

The emission rates of tritium and carbon-14 were estimated based on empirical ratios between radionuclide contents in the waste and releases [7-27]:

- HTO: 1% of the inventory per year, based on historical operational data [7-27]. The methodology, including physical processes are discussed in [7-27].
- C-14: 0.07% of the inventory per year, based on historical operational data [7-27]. The methodology, including physical processes are discussed in [7-27].

Emissions of Radon were evaluated using RESRAD OFFSITE software, accounting for ingrowth in the disposed waste and migration through the waste material. The methodology, including physical processes in calculations, is described in Appendix C of the user's manual for RESRAD (onsite) [7-28].

The resulting airborne emission rates, calculated based on the inventory presented in Section 4.2, are summarized in Table 7-1. These emission rates account for the presence of the gas venting system, which would allow gas to escape the mound regardless of any cover that is in place, as they ignore the temporary cover/cap entirely. The airborne emission rates provided in Performance Assessment Report revision R0 [7-29], were updated based on the revised waste/fill volume in ECM of 1,380,000 m^3. Performance Assessment Report revision R0 [7-29] originally used volume in ECM of 1,820,000 m^3. Therefore, the airborne emission values in Table 7-1 was reduced by a factor of 1,380,000/1,820,000.

Table 7-1 Airborne Emission Rates under Normal Conditions

Radionuclides	Airborne emission rate (Bq/s) at year 2070
H3	9.39E+03
C-14	7.43E+02
Radon	3.16E-03

7.2.4 Radiological Emissions to Water

Throughout the pre-closure period, during operations of the NSDF, there will be one active cell, partially filled in with waste. The remaining cells will be in one of the following states:

- Awaiting construction.
- Under construction or empty.
- Filled in with radioactive waste and closed using an engineered cover.

During this time, the bulk waste placed into the active cell will be exposed to precipitation. There is a daily cover, however rain onto an exposed cell is still considered as contact water. Thus, some contaminated leachate will be generated as a result of contact of precipitation and run-off with the waste. The function of the base liner and leachate collection system is to ensure that all generated leachate is collected and transferred to the WWTP for treatment.

Collected leachate and decontamination effluents resulting from the cleaning of vehicles and similar activities will be directed to the WWTP for treatment. Radionuclide composition of the combined influent will be dominated by leachate. Following treatment, the WWTP wastewater will be discharged into the infiltration area in the northern section of the NSDF site.

Small quantities of residual contaminants will thus, enter the groundwater. These contaminants will be transported via East Swamp Stream and Perch Lake towards Perch Creek, which feeds into the Ottawa River.

The concentrations of radionuclides in the WWTP effluent will meet CNL's discharge limits, as presented in Table 7-2 [7-30] and [7-31].

This is a conservative, bounding assumption as the majority of releases will be below these limiting values. In this version of Performance Assessment Report, Th-232 was added to Table 7-2.

Table 7-2 Maximum Concentrations of Radionuclides in the WWTP Wastewater [7-30]

Radionuclide	Concentration (Bq/L)
Ag-108m	60
Am-241	0.7
Am-243	0.7
C-14	200
Cl-36	100
Co-60	40
Cs-135	70
Cs-137	10
H-3[4]	1.4E5
I-129	1
Mo-93	40
Nb-94	80
Ni-59	2000
Ni-63	900
Np-237	1
Pu-239	0.6
Pu-240	0.6
Pu-241	0.6
Pu-242	0.6
Ra-226	0.5
Se-79	50
Sn-126	30
Sr-90	5
Tc-99	200
Th-232	0.6
U-233	3
U-234	3
U-235	3
U-238	3
Zr-93	5

[4] HTO concentration in leachate, as presented in Table 7-2, was estimated based on the projected inventory of tritium in bulk waste. This does not account for waste, which may be placed into specialized containers, designed to minimize potential emissions of tritium, or decay-stored prior to placement into the ECM.

Releases of tritium represent a special case as tritium in the form of HTO will not be removed from the leachate during processing at the WWTP via filtration and IX treatment. For this reason, concentration of tritium in effluent was estimated based on its inventory in bulk waste, leachate generation rate and the total quantity of waste water.

7.2.5 Selection of Potential Critical Groups

Doses were calculated for a number of human receptors represented by members of PCGs as described in Section 3.1. Specifically, two types of PCGs were identified based on proximity and characteristics that may result in elevated exposures:

- Residential (homes established on the shore of the Ottawa River and communities that are serviced with water drawn from the Ottawa River).
- Seasonal (cottages on the shore of the Ottawa River).

The age class affects the PCGs habits, intake rates and dose coefficients, which in turn impact dose calculations. Accordingly, PCGs were categorized into three age classes as defined in CSA N288.1-14 [7-1], i.e. adult, child and infant.

7.2.6 Estimated Doses to Members of the Public

Doses to individual members of PCGs were calculated using the IMPACT 5.5.1 software, taking into account both waterborne and airborne emissions. Resulting estimates of potential radiological exposure of members of the public during operation of the NSDF are presented in Table 7-3 and Table 7-4 for waterborne and airborne pathways, respectively. Total exposure is summarized in Table 7-5.

The doses to PCGs reported in Table 7-3 were revised from doses in Performance Assessment Report R0 [7-29] based on the revised treated waste flowrate of 10,024 m3/y. In addition, the dose from Th-232 was also included. The original Table 7-3 in Performance Assessment Report R0 [7-29] mistakenly reported the maximum dose from one radionuclide instead of the sum of the doses for all radionuclide. This has been fixed in this document. In order to calculate the dose for each receptor, the dose rate for unit emission (estimated by the IMPACT model) was multiplied by the actual emission values (Bq/s). The actual emission values were calculated using the radionuclide concentrations in the treated wastewater, the leachate flowrate, and the dilution factor in the river.

The doses to PCGs reported in Table 7-4 were revised from doses in Performance Assessment Report R0 [7-29] based on the revised emission rates provided in Table 7-1. The revised emission rates were smaller by a factor of 1,380,000 / 1,820,000. Revised waste/fill volume in ECM is 1,380,000 m^3, while Performance Assessment Report revision R0 [7-29] originally used volume of 1,820,000 m^3.

Table 7-3 Dose to PCGs Due to Waterborne Emissions, Normal Operations

Receptors	Adult (mSv/y)	10 year old Child (mSv/y)	One year old infant (mSv/y)
Cottager	1.4E-07	1.4E-07	1.0E-07
Pembroke	2.8E-06	3.2E-06	5.0E-06
Petawawa	3.0E-06	3.4E-06	5.3E-06
Laurentian Valley	2.7E-06	3.1E-06	5.1E-06

Table 7-4 Dose to PCGs Due to Airborne Emissions, Normal Operations

Receptors	Adult (mSv/y)	10 year old Child (mSv/y)	One year old infant (mSv/y)
Balmer Bay	5.7E-06	6.7E-06	1.0E-05
Chalk River	5.4E-06	8.5E-06	1.6E-05
Cottager	5.0E-06	4.2E-06	4.4E-06
Deep River	2.4E-06	4.2E-06	8.3E-06
Mountainview	2.7E-06	4.4E-06	8.4E-06
Pembroke	3.2E-07	5.0E-07	9.4E-07
Petawawa	2.5E-07	4.5E-07	8.9E-07
Laurentian Valley	3.3E-07	5.0E-07	9.3E-07

Table 7-5 Total Doses to PCGs due to Exposure to Radiological Emissions during Normal Operations

Receptor	Adult (mSv/y)	10 year old Child (mSv/y)	One year old infant (mSv/y)
Balmer Bay	5.70E-06	6.70E-06	1.00E-05
Chalk River	5.40E-06	8.50E-06	1.60E-05
Cottager	5.14E-06	4.34E-06	4.50E-06
Deep River	2.40E-06	4.20E-06	8.30E-06
Mountain view	2.70E-06	4.40E-06	8.40E-06
Pembroke	3.09E-06	3.68E-06	5.99E-06
Petawawa	3.26E-06	3.87E-06	6.23E-06
Laurentian Valley	3.01E-06	3.63E-06	5.98E-06

The table indicates that the maximum estimated dose to members of PCGs is 1.6E-05 mSv/y to members of the critical group, which is represented by a one year old infant in Chalk River with airborne releases being the major contributors. Residents of Chalk River are located upstream from the Perch Creek outflow into the Ottawa River and are not exposed to the waterborne pathway. This maximum dose to the Critical group is estimated to be less than 0.01% of both the regulatory dose limit of 1 mSv/y and the licensing limit of 0.3 mSv/y.

7.3 Assessment of Doses to Non-Human Biota

7.3.1 Methodology

Non-human biota in the vicinity of the ECM could be exposed to airborne and waterborne emissions as well as direct gamma radiation from the waste. Airborne emissions consist of gaseous HTO, C-14, and Radon released from unsealed packages. All contaminated leachate, contact water and decontamination effluents will be treated at the WWTP. Treated effluent from the WWTP will be released in the infiltration area north of the ECM, from where small quantities of residual contaminants will migrate towards the East Swamp Stream. The Stream discharges into Perch Lake, which is connected to the Ottawa River through Perch Creek (see Section 3.2 for additional information). Residual contaminants from the WWTP effluent will be most concentrated with the East Swamp Stream, before traveling through Perch Lake, Perch Creek and onto Ottawa River. Doses to non-human biota exposed to the aquatic habitat of East Swamp Stream were calculated to provide a bounding estimate of potential exposure.

A comprehensive framework for assessing radiological exposure to Non-Human Biota is provided in the CSA Environmental Risk Assessment N288.6-12 [7-2]. The standard addresses the assessment of doses to Non-Human Biota from on-going operations however, a similar approach can be used for Predictive Effects Assessment.

The assessment process includes the following steps:

1. Characterization of the existing environment (Section 3).
2. Determination of potential contamination and physical stressors resulting from the project (current section).
3. Identification of VCs and selection of receptors (Section 3.9.2).
4. Selection of assessment criteria (Section 2.5).
5. Prediction of potential environmental effects by characterizing the risks to ecological receptors (current section).

Ecological receptors could be exposed to radiation by external gamma radiation and a variety of environmental exposure pathways which are detailed in Section 7.3.2.

7.3.2 Ecological Conceptual Model and Exposure Pathways

The pathways considered for ecological receptors include exposure to air, water, soil, sediment, and various dietary components for different species. This is illustrated in Figure 7-2 and Figure 7-3.

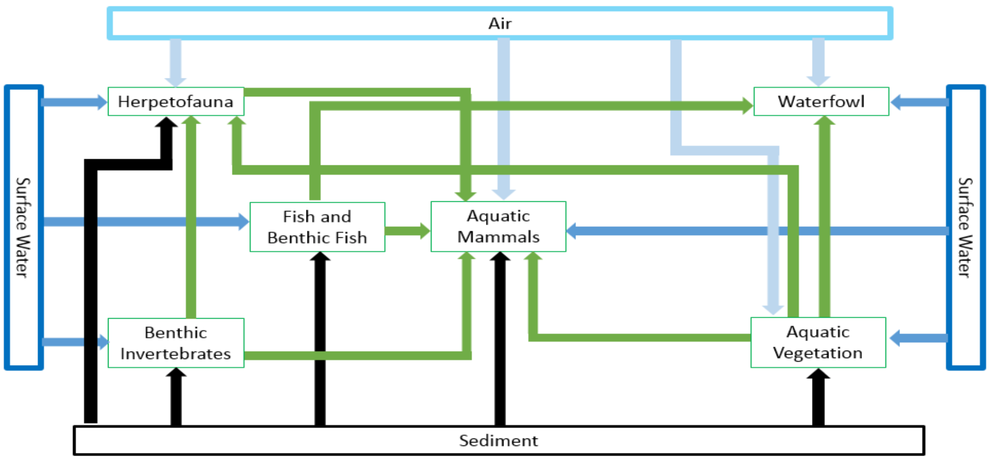

Figure 7-2 Exposure Pathways for Aquatic Non-Human Biota Exposure

Note: Interactions within receptor category are not shown.

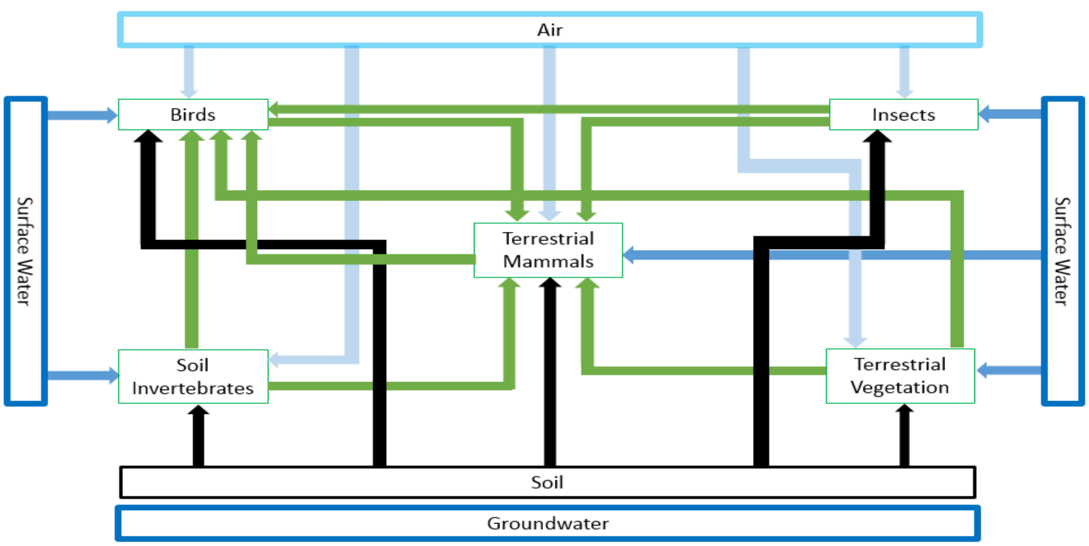

Figure 7-3 Exposure Pathways for Terrestrial Non-Human Biota Exposure

Note: Interactions within receptor category are not shown.

For each pathway, doses were calculated in accordance with CSA N288.6-12 [7-2]. The calculation of internal and external doses due to the exposure from all environmental pathways is discussed below.

7.3.3 Calculation of Internal Dose

Internal dose is calculated as follows:

$$D_{int} = DC_{int} \times C_t$$

Where

D_{int} = internal dose rate (µGy/day)

DC_{int} = internal dose coefficient for aquatic or terrestrial organism (µGy/day per Bq/kg)

C_t = radionuclide concentration in tissue of the aquatic or terrestrial organism (Bq/kg)

The key to the calculation of the internal dose to any organism is to obtain the concentrations of radionuclides in the tissue of the organism (referred to as tissue concentration). The tissue concentration could be determined based on the measurement of field samples. If monitoring data is not available, the tissue concentration can be derived based on environmental media concentrations and transfer factors. Specifically, for plants, invertebrates and fish, the tissue concentration can be calculated with the following equation:

$$C_t = C_m \times BAF$$

Where

Ct = tissue concentration[5] (Bq/kg)

Cm = environmental media concentration (Bq/L or Bq/kg)

BAF = indicator-specific, media-dependent bioaccumulation factors (L/kg or kg/kg)

For birds and mammals, the tissue concentration can be calculated with the following equation:

$$C_t = \sum (C_x \times I_x \times TF)$$

Where for a given radionuclide,

Cx = concentration in the food chain item, x, of the bird or mammal (Bq/kg)

Ix = ingestion rate of the food item, x (kg/day)

TF = indicator-specific transfer factor (d/kg)

7.3.4 Calculation of External Dose

The equations to calculate external dose are as follows:

For aquatic organisms

External dose to aquatic organisms can be calculated with the following equation:

$$D_{ext} = DC_{ext}\{[OF_w+0.5 \times OF_{ws}+0.5 \times OF_{seds}] \times C_w+ [OF_{sed}+0.5 \times OF_{seds}] \times C_s\}$$

Where

[5] Note that the concentration data in this document are for fresh weight (fw).

D_{ext} = external dose rate (µGy/day)

DC_{ext} = external dose coefficient (µGy/day per Bq/kg)

C_s = radionuclide concentration in sediment (Bq/kg)

C_w = radionuclide concentration in water (Bq/L)

OF_w = fraction of time in water (unitless)

OF_{ws} = fraction of time on water surface (unitless)

OF_{sed} = fraction of time in sediment (unitless)

OF_{seds} = fraction of time on sediment surface (unitless)

For terrestrial organisms

External dose to terrestrial organisms can be calculated with the following equation:

$$D_{ext} = DC_{ext,s} \times OF_s \times C_s + DC_{ext,ss} \times OF_{ss} \times C_{ss}$$

Where

D_{ext} = external dose rate (µGy/day)

$DC_{ext,s}$ = external dose coefficient for exposure in soil (µGy/day per Bq/kg)

$DC_{ext,ss}$ = external dose coefficient for exposure on soil surface (µGy/day per Bq/m^2)

C_s = radionuclide concentration in soil (Bq/kg)

C_{ss} = radionuclide concentration in soil surface (Bq/m^2)

OF_s = fraction of time in soil (unitless)

OF_{ss} = fraction of time on soil surface (unitless)

The values of the parameters in the equations are discussed further.

7.3.5 Dose Coefficients

The International Commission on Radiological Protection (ICRP) 108 [7-32] provides the Dose Coefficients (DC) for the reference plants and animals.

For internal dose coefficients, the following weighting factors are used for tritium and alpha emitters:

- For tritium, the weighting factor, or relative biological effectiveness, a value of 2 is used to calculate the weighted internal DC.
- For other radionuclides, the weighted internal DCs are calculated as follows:

Weighted DC = (unweighted DC x fraction of alpha component x 10) +
(unweighted DC x (1-fraction of alpha component)

The value of the fraction of alpha component for a specific radionuclide is available in ICRP 108 [7-32].

7.3.6 Transfer Factors

In this assessment, the Bioaccumulation Factor (BAF) and Transfer Factor (TF) are used to estimate radionuclide concentrations in indicator species. This is consistent with CSA N288.6-12 [7-2]. The BAF and TF consist of the following:

- Transfer from water to fish, aquatic plant, amphibian, and benthic invertebrate.
- Transfer from soil to invertebrate.
- Transfer from air and soil to plant.
- Transfer from air (inhalation), soil (intake), water (intake), and foodstuff to mammal and birds.

The primary references for the TFs are as follows:

- ICRP 114 [7-33].
- CSA N288.1 -14 [7-1].

7.3.7 Evaluation of Environmental Concentrations

All contaminated leachate, contact water and decontamination effluents will be treated at the WWTP. Treated effluent from the WWTP will be released in the infiltration area north of the ECM, where small quantities of residual contaminants will migrate towards East Swamp Stream. The concentrations of radionuclides in the WWTP effluent are predicted to meet the CNL's discharge limits, and are presented in Table 7-2. The concentrations of radionuclides in the East Swamp Stream can be derived by applying a dilution factor of 0.12, which was calculated based on the flow rate of 7.2E4 m^3/y in East Swamp stream [7-24] and the WWTP effluent flow rate of 10,024 m^3/y.

Both aquatic and terrestrial species will be exposed to contaminated surface water and sediment in the East Swamp stream, Perch Lake, Perch Creek, and Ottawa River. As significant dilution will occur in the Perch Lake, Perch Creek and Ottawa River, exposure within the aquatic environment of the East Swamp stream is bounding during the period of leachate management system and WWTP operations. Therefore, doses to non-human biota which are exposed to East Swamp stream are evaluated.

7.3.8 Radiological Emissions-Airborne

Gaseous radionuclides will be released to the atmosphere during normal operations, as described in Section 7.2.3. The emission rates of these radionuclides are presented in Table 7-1.

The concentrations of HTO and C-14 in air were estimated using the IMPACT code. The estimated concentrations were then used to calculate dose to terrestrial species.

7.3.9 Doses to Non-Human Biota

Doses to non-human biota were calculated based on the waterborne and airborne emissions from the ECM. In addition, external gamma dose due to direct exposure to the waste was taken into account. It was conservatively assumed that all species would be exposed to a gamma dose rate of 10 µGy/h, which is based on the dose constraint of 10 µSv/h at the NSDF fence line. The results are presented in Table 7-6.

The predicted doses to all indicator species of concern are below the dose benchmark values. Dose to Bald Eagle, the most exposed species, is estimated to be 31 µGy/h, accounting for 31% of the benchmark value for terrestrial species.

The doses due to airborne emissions reported in Table 7-6 were revised from doses in Performance Assessment Report R0 [7-29] based on the revised emission rates provided in Table 7-1. The revised emission rates were smaller by a factor of 1,380,000 / 1,820,000. Revised waste/fill volume in ECM is 1,380,000 m3, while Performance Assessment Report revision R0 [7-29] originally used volume of 1,820,000 m3. In addition, the updated treated leachate flowrate (10,024 m^3/y) was used to calculate the emission to surface water. The dose rates for unit emission from IMPACT Model were used for dose calculations.

Table 7-6 Doses to Non-Human Biota

Taxa	Indicator	Dose due to direct exposure (µGy/h)	Dose due to waterborne emission (µGy/h)	Dose due to airborne emission (µGy/h)	Total dose (µGy/h)	Benchmark (µGy/h)	% of Benchmark
Aquatic Plant	Reed	1.0E+01	1.1E+02	0.0E+00	1.2E+02	400	30%
Fish	Bluntnose minnow	1.0E+01	1.1E+02	0.0E+00	1.2E+02	400	30%
	Black Bullhead	1.0E+01	1.0E+02	0.0E+00	1.1E+02	400	28%
	Pike	1.0E+01	1.0E+02	0.0E+00	1.1E+02	400	28%
Terrestrial Plant	Red Maple	1.0E+01	0.0E+00	1.8E-03	1.0E+01	100	10%
Insect	Monarch Butterfly	1.0E+01	0.0E+00	1.7E-03	1.0E+01	100	10%
Mammal	Little brown Myotis	1.0E+01	2.1E-02	2.4E-03	1.0E+01	100	10%
	Meadow Vole	1.0E+01	2.2E-02	4.7E-04	1.0E+01	100	10%
	White-tailed deer	1.0E+01	2.1E-01	2.0E-03	1.0E+01	100	10%
	Short-tailed Shrew	1.0E+01	2.2E-02	9.1E-04	1.0E+01	100	10%
	Eastern Wolf	1.0E+01	6.1E-01	4.0E-03	1.1E+01	100	11%
Reptile	Snapping Turtle	1.0E+01	1.8E+01	0.0E+00	2.8E+01	100	28%
	Common Watersnake	1.0E+01	1.0E+01	0.0E+00	2.0E+01	100	20%
	Eastern Milksnake	1.0E+01	0.0E+00	7.5E-04	1.0E+01	100	10%
Amphibian	Green Frog	1.0E+01	1.8E+01	0.0E+00	2.8E+01	100	28%
Bird	Canada Warbler	1.0E+01	1.1E-02	2.5E-03	1.0E+01	100	10%
	Eastern Whip-poor-will	1.0E+01	1.2E-02	2.5E-03	1.0E+01	100	10%
	Purple Finch	1.0E+01	1.2E-02	1.9E-03	1.0E+01	100	10%
	Ruffed Grouse	1.0E+01	1.3E-02	5.0E-04	1.0E+01	100	10%
	Belted Kingfisher	1.0E+01	9.6E+00	2.8E-06	2.0E+01	100	20%
	Bald Eagle	1.0E+01	2.1E+01	8.9E-05	3.1E+01	100	31%
	Mallard	1.0E+01	1.2E+01	2.8E-06	2.2E+01	100	22%
	Great Blue Heron	1.0E+01	1.7E+01	2.8E-06	2.7E+01	100	27%
Invertebrate	Earthworm	1.0E+01	0.0E+00	7.5E-04	1.0E+01	100	10%
	Crayfish	1.0E+01	4.0E+01	0.0E+00	5.0E+01	400	13%

7.3.10 Cumulative Effects

Wastewater releases from the NSDF will impact the Perch Lake Basin. Although there are no new or planned facilities other than the NSDF that may impact the Perch Lake Basin, many of the site's existing WMAs, including WMAs A and B and the LDA (which includes Reactor Pit 1, Reactor Pit 2, Laundry Pit and the Chemical Pit) are in this basin (see Section 1.4). Contaminants are transported via groundwater to nearby wetlands, including East Swamp, which will be the recipient water body for the NSDF wastewater.

Contaminants released into the Perch Lake Basin migrate to Perch Creek from where they reach the Ottawa River (see Figure 1-6), which is the ultimate receptor for all CRL discharges.

In 2015, the total estimated dose to the public for all liquid effluent exposure pathways represented 0.1% of the regulatory public dose limit of 1 mSv [7-24]. The 2015 total estimated dose for all air effluent exposure pathways represented 8.2% of the regulatory public dose limit. It is conservatively estimated that the NSDF may contribute 0.01% of the regulatory public dose limit from air and liquid effluent pathways (Section 7.2.6). The potential NSDF contribution would be very minor compared to the current exposures.

Similarly, the NSDF's contribution to potential impacts on populations of non-human biota in the Perch Lake Basin does not result in unacceptable cumulative effects. East Swamp was identified in the Ecological Risk Assessment as one of the areas where aquatic ecological receptors are potentially at risk from exposure to Sr-90 [7-34]. The highest average estimated dose for East Swamp is 10,200 μGy/d or 425 μGy/h for the snail. Potential contribution from the NSDF to the dose of aquatic species is estimated to be less than 1% of this value (see Section 7.3). Estimated doses resulting from historic contamination due to releases from WMAs and LDAs, fall below benchmark values for Perch Lake and Perch Creek [7-34].

In summary, potential contribution from the NSDF to exposure of aquatic species is less than 1% of the current levels of exposures.

7.4 Accident Assessment

An accident is defined as any unintended event, including operating errors, equipment failures or other mishaps, the consequences or potential consequences of which are not negligible from the point of view of protection or safety. The scope of this accident analysis is to analyze initiating events/hazards that have the potential to result in radiological consequences to the environment which includes external events and internal failures relating to malfunctioning of the NSDF systems and components. This includes both pre-closure failures, which may occur during operation of the NSDF and post-closure events, which may lead to increases in radioactive releases to the environment after closure and following the end of Institutional Control. This accident assessment has been developed based on the 100% design.

Identification of relevant hazards is provided in Section 7.4.2. The assessment of consequences for initiating events that may occur during pre-closure are provided in Section 7.4.3. Analysis of consequences resulting from disruptive events and scenarios during post-closure can be found in Section 8.

The accident assessment is conducted in two steps:

1. Identification and screening of internal and external hazards.
2. Accident analysis for all scenarios corresponding to hazards that were screened in during Step 1.

7.4.1 Methodology

Hazards that are considered for the screening analysis can be of two types; External and Internal Hazards.

External hazards are defined as hazards that are initiated outside the NSDF site boundary or are natural hazards, which are outside CNL direct control. These hazards could be in the form of natural hazards (ice-storms, flood, etc.) or man-made hazards (human intrusion, aircraft crash, etc.). These hazards could have impact on the containment of radioactive waste and functioning of other safeguards.

Internal hazards are defined as hazards that are initiated within the boundary of the NSDF site and are not natural hazards.

The scope of this assessment does not include evaluation of the following events/conditions:

- Hazards originating in or affecting the adjacent facilities (i.e. other facilities on the CRL site but outside of the NSDF site).
- Malevolent acts.

Conventional hazards not involving radioactive materials and other events affecting occupational safety are identified. If further analysis is required to evaluate potential consequences of non-radiological hazards, it will be carried out in the EA.

The hazard identification work involved a literature review to locate all documents and guidance that would be useful in developing a full list of the hazards to be considered for a NSDF. No prior assumptions were made as to which hazards should be included or excluded. Some of the documents that have been consulted as part of this literature review are listed below:

- Port Hope EA Study Report [7-35].
- Port Granby EA Study Report [7-36].
- Chalk River WMA Hazard Identification Report [7-37].
- Ontario Power Generation’s Low and Intermediate Level Waste Repository – Preliminary Safety Assessment [7-27].
- Idaho CERCLA NSDF PA [7-38].
- CANDU Owners Group and CNL Operating Experience Reports.
- IAEA Safety Series No. 50-P-7; Table 1 [7-39].
- IAEA Specific Safety Guide SSG-3 [7-40].
- IAEA Safety Series No. 50-SG-S9 [7-41].

- NUREG/CR-2300; Table 10.1 [7-42].
- NUREG/CR-4839 [7-43].
- NUREG 1407 [7-44].

The identification process included an initial screening to remove initiators that clearly are not credible events for the NSDF and therefore, do not require a consequence assessment. Events considered, but discarded during the initial screening are listed for completeness, along with the rationale for removing the event from further consideration. The initiating events and screening rationale are presented in Table 7-7 and Table 7-8 for external and internal radiological events, respectively.

The hazard analysis presented in this report is augmented in the NSDF SAR, using standard hazard identification techniques and a formal screening of FEPs.

The EA methodology requires identification of “credible events”, which are defined as Malfunctions and Accidents with a reasonable probability of occurrence (an example is provided in reference [7-27]). The latter is defined as commensurate with a frequency level exceeding 10^{-6} per year. The resulting list is subject to grouping of events. Only bounding events for each group of events are analyzed.

Radiological consequence assessments are conducted for the identified bounding accident during operations or for the normal evolution and disruptive scenarios during post-closure. Methodology and assumptions relating to the analysis of such scenarios are described in the respective sections.

7.4.2 Hazard Identification and Screening

The hazard screening process and findings are described in Table 7-7 and Table 7-8 for external and internal events respectively. Descriptions include rational for including or excluding each event from subsequent analysis as well as conclusions if the event requires assessment during pre-closure or post-closure. Analysis for pre-closure is provided further in Section 7, while events and scenarios requiring analysis during post-closure are assessed in Section 8.

Table 7-7 Events with Potential Radiological Consequences – External Events

Event	Screening Result and Rationale
Earthquakes	Consequence assessment required (Pre-closure). An earthquake may cause failure of one or several containment barriers in the ECM. It could lead to doses to workers and public due to dust dispersion and external exposure to gamma radiation in the event that the cover or berms fail following such an event. Waste could also become exposed to infiltration of precipitation and lead to groundwater contamination. The CRL site is located within the Western Quebec Seismic Zone, where minor seismic activity continues to occur. Site-specific seismic surveys were conducted in [7-45]. The ECM has been designed to withstand PGA at an annual exceedance frequency corresponding to 1 in 10,000 years. This means that failure of the berms and the engineered cover during the design life of the facility has a very low probability. The effect of a beyond design basis earthquake on the ECM has been considered in the Consequence of Failure document [7-46]. The event is considered to occur near the end of the operations phase, when 9 out of 10 cells have final cover and the last cell is open. At this time, the total activity in the ECM is at a maximum, and the total area of disposed waste without final cover is also at a maximum. Therefore, the radioactive material released is considered to bound scenarios for all other time periods. Parameters related to the worker and off-site public dose calculations are documented in the Consequence of Failure document [7-46]. The doses to workers and members of the public as a result of a severe seismic event at the ECM are 4E-03 mSv and 1E-03 mSv respectively. During operations, a seismic event may also impact systems and components associated with the leachate management and the WWTP. It is assumed that the event occurs just prior to the final cell being closed, when the maximum amount of leachate is generated from the ECM. Therefore, Cells 1 to 8 are closed with final cover, Cell 9 is closed with interim cover, and Cell 10 is open. The total radionuclide activity and uncovered waste area are maximized at this time. Additionally, due to a complete failure of the ion exchange and residuals handling systems, the entire quantity of spent resins and residuals are assumed to be spilled on the floor of the WWTP. As the WWTP building collapses, a fraction of the resins and residuals become airborne as a puff of radioactive material. Both the resins and residuals have a high moisture content, and therefore the fraction that becomes airborne is small. Additional parameters pertaining to the calculation of dose for workers and members of the public are provided in the Consequence of Failure document [7-46]. The doses from a severe seismic event at the WWTP are calculated to be 9E-03 mSv and 0.04 mSv respectively. Additional details can be found in [7-45].

Event	Screening Result and Rationale
Flooding	Consequence assessment not required (Pre-closure). Flooding due to precipitation runoff It is a design requirement for the NSDF to incorporate 2 year, 5 year, 10 year, 25 year, 50 year, and 100 year (or prevailing Regional) precipitation storm events [7-45]. The criterion of concern for potential site inundation and spread of contamination is the PMP, which represents the most severe possible rainfall event for a given location. While PMP is not defined as a probabilistic event, it represents the worst possible scenario, and therefore encompasses all credible precipitation events. By extension, any precipitation event that is greater than the PMP is not credible (i.e. is assumed to have probabilities of less than 10^{-6}), and as such, is less than the 10^{-6} credibility screening criterion. All drainage features have been designed to safely convey the flows associated with the PMP event [7-47]. This will remove excess water and prevent potential spread of contamination during the period of the NSDF operations. Three liquid storage tanks, with a total capacity of 5,678.1 m^3, will be installed near the ECM footprint [7-48]. The WWPT system has been designed with the capacity to contain contact stormwater that would be produced from the largest cell of the ECM (only one cell would be open at any given time) from *two* back-to-back 100-year, 24-hour storm events, as well as leachate from closed cells and impacted wastewater from ongoing site operations. Flooding due to river water level rise Regarding flooding from the river, the Ontario Ministry of Natural Resources calculated a conservative estimate of the 100-year flood elevation for this reach of the Ottawa River at 115 m. The highest and lowest recorded levels of the river at CRL are 113.6 m (1979 April) and 110.6 m (1971 August) above sea level, respectively [7-49]. The area of the NSDF was characterized as having ground surface elevations ranging from a low of approximately 160 mASL to a high of 196 mASL [7-50]. Therefore, the NSDF site is located beyond the Ottawa River flood plain and riverine flooding is not credible. Flooding due to sudden releases of water from natural or artificial storage No large lakes are located within the drainage areas in the vicinity of the NSDF that could influence flooding events. Perch Lake is sufficiently remote that due to topographical features, it cannot cause flooding of the ECM. The design basis event for failure of artificial storage is failure of the Ontario Power Generation Des Joachims Generation Dam located 28 km upstream of CRL at Rolphton. The maximum river level from dam failure is estimated to be 126 mASL [7-49]. This is below the lowest ground surface elevation at the NSDF site, which is 160 mASL. Therefore, flooding due to sudden releases of water is not

Event	Screening Result and Rationale
	credible. Flooding due to other causes Flooding events due to waves, seiche, tsunami, and ice-jamming are not credible due to lack of large waterbodies in the vicinity of the site.
Extreme temperature	Consequence assessment not required (Pre-closure). Maximum and minimum design temperatures for CRL site are 30°C and -32°C, respectively [7-51]. During pre-closure, the effects from low or high ambient temperature are mitigated by design. All NSDF equipment and structures are required to operate correctly under extreme temperatures as specified in the CRL Site Characteristics document [7-51]. Acceptable weather conditions are to be defined for waste loading operations, such that operations do not take place during extreme cold and the required waste compaction ratio can be achieved. Monitoring, which will be in place during the NSDF operational period, will identify any possible weather-induced damage to the NSDF cover or liners so that the issue can be quickly mitigated. Therefore, no credible accidents have been identified for the operational period. The leachate storage tanks will be equipped with an electric heater and a temperature control system to ensure that the contents do not freeze in winter. Adequate reliability of the heater and back-up power will be ensured to minimize failure frequency. This will apply also to the heater "ON" failure mode which would result in overheating of the tank contents. Containment will be provided to ensure that tank leachate does not spread in the event of a spill. In the same manner, trace heating will be provided for any exposed piping that will be transferring radioactive liquids.
Snowpack	Consequence assessment not required (Pre-closure). Maximum snow load for the CRL site is 2.5 kPa [7-51]. Design calculations demonstrate that operational facilities will be able to withstand maximum snow loads during the pre-closure period for a 100-year return period event [7-47]. While a beyond-design event is credible, the consequences of such an event would be limited to a roof collapse of the WWTP or auxiliary facilities. This may lead to spills of radioactive or toxic effluent. However, it is expected that temporary storage areas have been provided with sufficient sump capacity to collect accidental spillage and that berms are constructed as needed to ensure that any spillage is retained within the temporary storage areas. Therefore, this hazard cannot lead to unacceptable radiological consequences.

Event	Screening Result and Rationale
High Wind	Consequence assessment not required (Pre-closure). High winds can cause structural damage due to wind pressure or airborne missiles. High winds may occur on a large scale as a result of extra-tropical storms or low pressure systems or on a small scale as a result of thunderstorms. They generally fall into three categories: Thunderstorm Winds Extra-Tropical Storms (Hurricanes) Tornadoes Design Basis Tornado for the CRL site has been selected as an EF2 Tornado with maximum wind speed of 225 km/hr [7-51]. This corresponds to a 10^{-5}/y frequency. If a beyond design basis high wind event were to occur, it is not expected to impact disposed radioactive waste in *closed* cells, as the engineered mound will not be susceptible to its effects. The cover system design will prevent any windblown projectiles from reaching the geomembrane or the base liner components. The daily temporary cover system installed on *open* cells (those in operation) would similarly protect the emplaced wastes from a tornado. For on-site workers caught in the tornado, the dose received would be trivial compared to the mechanical hazards associated with a tornado. For members of the public, consequences would be bounded by those of fire scenarios (based on constant wind speeds blowing towards these receptors). Fire consequences are bounding because the source term that would be susceptible to a tornado would be limited to the material in the temporary storage area - similar to forest fire scenarios – and therefore the source terms are the same for these scenarios. With equal source terms, differences are due to dispersion. The dispersion factor for the fire scenario is 1.1×10^{-4} Bq/m^3 per Bq/s at the nearest public receptor location (3 km), whereas the dispersion factor for the tornado scenario is 4.5×10^{-6} Bq/m^3 per Bq/s (at 3 km) per Bq/s. Although the WWTP may be damaged if a beyond-design basis event were to occur during pre-closure period, gusts of winds would disperse any airborne radioactivity. For this reason, the effects would be bounded by other accident scenarios, such as fire. Any spills would be contained by berms which have been designed for this purpose. A beyond design high wind or tornado event may result in a spill of radioactive leachate from above-ground storage tanks due

Event	Screening Result and Rationale
	to missile impact or wind pressure. The tank storage area has been designed to contain potential spills. Radiological consequences of such an event, if any, would be bounded by other accident scenarios.
Ice Storms	Consequence assessment not required (Pre-closure). Ice-storms occur when the atmosphere is layered with warm air above denser, cold air near the ground surface. Precipitation falls through the warm layer in the form of rain. The rain falls into the shallow cold layer and freezes. Ice storms occur frequently and their frequency exceeds the Screening Frequency Level (SFL). Ice storms will not affect the integrity of the ECM cover. An ice storm could temporarily affect access to the NSDF and disrupt maintenance activities. The storm could also damage off-site power supply and necessitate the use of standby Class III power to ensure normal operation of the WWTP. The WWTP has sufficient storage capacity to handle any build of leachate in the event of a site-wide power outage. Therefore, this hazard cannot lead to unacceptable radiological consequences.
Lightning	Consequence assessment required (Pre-closure). Lightning occurrence is quite frequent. Lightning flashes per year for Ottawa are reported to occur at a rate of 90 per 100 km^2 [7-51]. Given the total NSDF site area of 70 640 m^2 [7-52], this translates to an annual frequency of the NSDF site flashes of 0.06 1/y. Potentially vulnerable facilities and equipment include the WWTP, on-site generators, fuel storage area, and any temporary storage areas which may contain exposed combustible material, such as wood. These will represent a small fraction of the total NSDF site, likely less than 10 000 m^2, further reducing the probability of strikes to below 0.01 1/y. Lightning protection will be provided which typically ensures 99.5 to 99.9% protection [7-51]. Nevertheless, lightning strikes cannot be ruled out as incredible as the resulting frequency exceeds the SFL. Buried waste in the ECM will not be impacted by lightning strikes. Lightning strikes may damage off-site or on-site power supply and/or render the WWTP temporarily inoperable. Sufficient storage capacity will be provided for leachate to handle any build up. Lightning may also impact auxiliary facilities or temporary waste accumulation areas or cause surface vegetation fire, enhancing cover erosion during the post-closure period.

Event	Screening Result and Rationale
Meteorites	Consequence assessment not required (Pre-closure). The maximum number of meteorites that were found on the surface of the earth over a 5 year period is 50 [7-53]. It can be assumed that a meteorite has an equal chance of falling anywhere onto the Earth's surface, which is conservative for mid-latitude regions. Given the surface area of the earth of 510 072 000 km^2, and the total NSDF site area of 70 640 m^2 [7-52], the annual frequency of meteorite strikes can be estimated as 1.4E-9 1/y. This is below the SFL; therefore, no further assessment is required. The seismic event at the ECM analyzed in the Consequence of Failure analysis [7-46] includes a sensitivity analysis that considers the 100% displacement of waste at the end of the Operations period (i.e., the time of maximum activity in the ECM). The analysis indicates that the annual dose to members of the public resulting from leachate directly entering the groundwater system is less than 1 mSv/y.
Accidents at adjacent nuclear facilities	Consequence assessment not required (Pre-closure). An accident at nuclear facilities operating at the CRL site or radioactive waste storage facilities in WMA, may temporarily limit occupancy at the NSDF site. This would render the WWTP temporarily inoperable. Sufficient storage capacity is available to handle and leachate buildup. There will be no radiological consequences arising from operation of the NSDF as a result of such an event.
Forest fire	Consequence assessment required (Pre-closure). Wildland and forest fires could initiate from ignition sources such as ground maintenance activities, trees falling over transmission lines and lightning strikes during the fire season. Fire season is defined as April 1st to October 31st [7-54]. The characteristic used to measure this is called "depth of lethal heat penetration". A temperature of 60 degrees C is referred to as depth of lethal heat penetration. For high intensity brush or forest fires, the maximum depth of lethal heat penetration is 5 cm. The thickness of the engineered cover over the waste (for *closed* cells) is more than 1 m. Therefore, once an engineered cover is in place over the ECM cells, forest fires would pose no direct threat to the disposed wastes. This was demonstrated during the forest fire in 2016 June in Fort McMurray when the LLW disposal mound remained unaffected. Waste that has been emplaced in an *open* cell would also not be susceptible to forest fires because *open* cells are still covered with a daily cover material that is sufficiently thick to protect the waste. Lastly, were a fire to occur in an open cell during waste emplacement activities, it would be dealt with immediately (a larger fire would be bounded by the bounding fire

Event	Screening Result and Rationale
	scenario – see below, and Section 7.4.3.1). Therefore, waste in cells is not considered to be susceptible to a fire. However, during the NSDF operation, it is possible that waste placed in temporary storage - prior to emplacement in the disposal cell - could be impacted. This may lead to radionuclide releases to the atmosphere and potential environmental consequences. Once in disposal cell, fire is mitigated by the use of a daily soil cover over top of any emplaced waste in order to minimize the quantity of waste exposed. The bounding accident scenario for a forest fire would therefore involve the maximum inventory of radioactive waste that could be in temporarily storage (i.e. 590 m^3 of bulk waste and 90 m^3 packaged contact-handleable waste). It is assumed fire burns for 1 hr before being extinguished by CRL or off-site emergency responders. Additional details regarding the dose calculation parameters are presented in the Consequence of Failure document [7-46].
Aircraft crash	Consequence assessment not required (Pre-closure). There are no major international airports close to CRL; Ottawa being the nearest at 160 km away. There is a military airport at Canadian Forces Base Petawawa (12 km) and a civilian airport near Pembroke (22.5 km). There are two high level airways in the area, but low level airway movements do not contribute to the risk of an aircraft crash at CRL [7-51]. The frequency of an aircraft crash has been estimated as 1.9E-5 per year for the total area of Controlled Areas 1 and 2 (0.476 km^2) [7-51]. Given the much smaller area of the NSDF site (0.07 km^2), the frequency of an aircraft crashing at site is 2.8E-6 per year. Once the engineered cover is in place, disposed waste will not be vulnerable to this hazard. Any damage to the cover during pre-closure or monitoring periods would be repaired. Potential damage to the cover during the post-Institutional Control period due to plane crash would likely be repaired but it would also be bounded by human intrusion scenarios. While the WWTP and temporary storage areas may be impacted by an aircraft crash, the frequency of occurrence would be even smaller and consequences would be bounded by the Forest Fire scenario.
Power Failure	Consequence assessment not required (Pre-closure). Power failures can be caused by a number of events, from lightning to wildlife interacting with the offsite power lines. The consequences of a power failure would be those associated with shutdown of the WWTP until power was restored. As discussed for the failure of WWTP hazard (in Table 7-10 below), the maximum leachate generation rate prior to the NSDF closure has been estimated at about 10,024 m^3/year [7-26]. By comparison, on-site tank storage capacity would be in excess of 20,000 m^3 [7-52]. Given this relatively small volume, in the event of the WWTP shutdown the volume of fluid could be

Event	Screening Result and Rationale
	contained within the collection ponds until WWTP functionality is restored. Therefore, further assessment is required. The effects of power failures and their effects on operations were assessed in the "Safety Analysis Report" [7-5].
Subsidence	*Consequence assessment not required (Pre-closure).* Slope instability or subsidence may cause failure of containment barriers in the ECM. Subsidences are vertical earth movements, caused by undermining or failure of the underlying strata or by consolidation in areas in which the soil stresses increase materially. In a few cases, subsidences have been caused by underground erosion by artesian waters. Geotechnical conditions at the NSDF site are undergoing detailed characterization [7-50]. As a result of subsidence, stresses can be induced in the cover and geomembrane components due to settlement in the foundation soils, waste and the cover itself. The settlement calculation for the foundation and liner soils and the amount of settlement in the waste and cover will be evaluated in the detailed design. There is no historical evidence of subsidence at the NSDF site based on the geotechnical investigation performed so far. At this time, it has been concluded that there are no geotechnical conditions that would render the siting area unsuitable. The design shall provide geotechnical stability through adequate slope and foundation stability during construction, filling, closure, and post-closure.

Table 7-8: Events with Potential Radiological Consequences - Internal Events

Event	Screening Result and Rationale
Failure of the ECM containment system due to excessive settlement	Consequence assessment not required (Pre-closure). Excessive settlement of the waste within the ECM could damage the engineered cover, which would lead to increased water infiltration. However, based on the Conceptual WAC, and design requirements for provision of an appropriate slope and methods of placement [7-47] and [7-52], it can be concluded that future settlement will be very small. Furthermore, settlement within the ECM will be monitored for an extended period of time following closure and the effects of any initial settlement would be promptly corrected. Given settlement, if any, would occur during a comparatively short period after closure, and the regular inspections, maintenance and repair plans in effect for the ECM post-closure (during the Institutional Control period), it can be concluded that this hazard scenario is incredible and no consequence assessment is required. Grouting could also be considered to address this potential occurrence.
Failure of geomembrane in the cover	Consequence assessment not required (Pre-closure). Geomembrane and other components of the engineered cover have a 550-year design life [7-47].
Failure of liner	*Consequence assessment not required (Pre-closure)* The clay liner materials will be placed under rigidly-enforced quality control standards. Clay selected for the compacted clay liner will be tested for moisture content, gradation, Atterburg limits, maximum dry density, hydraulic conductivity, and leachate compatibility [7-52]. The secondary liner system will contain the leak detection system, which will operate during active Institutional Control. The sodium bentonite from the Geocomposite Clay Liner will provide a secondary protection layer below the HDPE geomembrane. The sodium bentonite will hydrate and seal with water contact to counteract any damage in the HDPE geomembrane. The underlying compacted clay is an extremely durable low-permeability material. The robust construction of the liner will ensure that the emplacement of waste will not cause damage to the liner; other damage to the liner (e.g. from an accident involving a dropped waste package) would be visible and would be immediately identified and addressed before continuing.
Failure of drainage system	*Consequence assessment not required (Pre-closure).* The primary and secondary granular drainage layers may undergo a decrease in hydraulic conductivity due to blockage by small particles. This would occur during early phases of construction and operation; the fines would eventually become fixed within the

Event	Screening Result and Rationale
	granular drainage layers and limit further intrusions and hydraulic conductivity reduction. Collection system pipes and any pumps may fail during construction or operation. Such failures would be immediately detected and repaired.
Release of stored energy	Consequence assessment not required (Pre-closure). The WWTP and other NSDF facilities may contain high energy pipes, valves and fittings that contain fluids (gas or liquid). A sudden release of stored energy could result in personal injury, equipment or property damage from explosion or fire and effects on the environment from uncontrolled release of contaminants. An accident scenario would involve a fire in the WWTP leading to a release of maximum radionuclide inventory that may be contained within the facility at any one time. However, the inventory that may be released as a result of this accident will be small compared to fire scenarios involving waste in temporary storage. Therefore, the latter scenarios will bound consequences for the release of stored energy scenarios.
Fire or explosion due to gas generation within ECM	Consequence assessment not required (Pre-closure). Radiolysis of reactive waste has a potential to generate toxic gases, vapours or fumes when mixed with water or is capable of detonation or explosive reaction. Such wastes would not be accepted for disposal at the NSDF. In any case, detonation would only result when the waste is subjected to a strong initiating source or heated under confinement. Landfill gas may form an explosive mixture, when it combines with air in certain proportions. Organic materials, such as wood, plastics and bitumen will be disposed within the ECM. This will result in the generation of methane, which would be created by the microbial decomposition of organic refuse. Underlying rock formation may also generate small quantities of natural methane. Methane is a flammable gas. Other flammable landfill gas constituents may include ammonia, hydrogen sulfide and non-methane organic compounds. Landfill gas is discussed in further detail in the Landfill Gas Management Plan [7-55]. There is a plethora of data on gas generation within municipal landfills, which typically contain large quantities of organic material. Methane Potential of AECL-MISC-295 per kg of refuse, has been estimated based on a comprehensive literature review [7-56]. This is likely conservative, based on data specific to radioactive waste disposal facilities. Methane releases would occur within the period of Institutional Control [7-56], declining over time as the organic waste degrades. Periodic measurements with a flammable gas meter are typically undertaken to ensure that flammable gas concentration does not exceed 10% of the lower explosive limit. For a fire or explosion to occur, methane and other flammable gases must accumulate in sufficient concentrations and there must be an ignition source. The NSDF has be designed so that the release and concentrations of flammable gases will be below regulatory limits. Provisions

Event	Screening Result and Rationale
	for the gas collection venting are included in the design [7-52]. Given that, and monitoring that will be undertaken during active Institutional Control, ECM explosion due to landfill gas generation is not considered credible.
Internal fire	Consequence assessment not required (Pre-closure). Flammable materials will be present at the NSDF, including fuels, oils and other combustible substances. Although unlikely, it is possible that a fire could break out, e.g. during welding construction activities, or as a result of the WWTP electrical systems malfunctioning. Fire detection and suppression systems will operate during construction and operations of the NSDF. If a fire were to be detected, Emergency Procedures would be followed. The CRL Fire Department will be notified as well as others working in the area. If an equipment fire were to occur, the consequences could be worker injury, burns and equipment damage. Safeguards to mitigate the risk of fire within the facility include proper storage of combustible materials, Fire Protection processes, Fire Department, portable fire extinguishers, and worker training. Bounding radiological consequences would be determined by the inventory of uncovered radioactive waste in temporary storage areas. This is consistent with the forest fire scenario; therefore, a separate consequence assessment is not required.
Release of toxic substances from WWTP	Consequence assessment not required (Pre-closure). It is not known if any toxic substances will be used at the WWTP. In the event there is any potential for the release of toxic gases, the monitoring program will include air quality monitoring to ensure that health and safety of personnel within the NSDF and environment are not compromised. Such a program will ensure that the air flow remains adequate for the equipment and activity involved.
Failure of WWTP treatment process	Consequence assessment not required (Pre-closure). The WWTP treatment process will involve several stages, including filtration, RO and evaporation. These are all well established, reliable technologies with a good track record in the industry. It is possible that the following treatment of leachate, contaminant concentrations will not achieve the required standards. The liquid will be sampled prior to release and would only be released once the desired standards are achieved. The liquid would be recirculated through the required treatment stages as required. Maximum leachate generation rate prior to the NSDF closure, has been estimated at about 10,024 m^3/year [7-26]. On-site tank storage capacity would be in excess of 20 000 m^3 [7-52]. Given the relatively small quantities of fluids involved, in the event of the WWTP not being fully functional, the fluids can be contained within the collection ponds until the WWTP functionality is fully restored.
Container drop	Consequence assessment not required (Pre-closure).

Event	Screening Result and Rationale
	It is possible that a radioactive waste package is dropped and damaged during on-site handling and emplacement operations. This may result in damage to shielding or containment, leading to localized contamination and personnel exposure. Any consequences would be bounded by either loss of shielding accident scenario or breach during on-site transfer.
On-site transfer accident	*Consequence assessment required (Pre-closure).* Radioactive waste transfers and temporary storage will take place during the NSDF operations. For the purposes of this assessment, it is assumed that: • The bulk waste will undergo temporary storage, up to a maximum volume of 590 m^3. • The packaged waste with higher activity waste will be transferred to the NSDF in batches of up to 10 packages per transfer (assumed to be 90 m^3 for assessment purposes). Although hazards arising from overland transfers of radioactive waste to the WMAs are covered by the current licence, the expected frequency of transfers to the NSDF will be significantly higher at the time of operations. A number of accident scenarios can be associated with the on-site transfer of waste. In particular, a fire could occur on board the waste transfer vehicle. This could be due to a fuel leak or vehicle impact/collision. In addition, packaged waste may fall and suffer damage as a result of an accident. Transfer vehicles will undergo regular checks and maintenance. Drivers will be expected to complete visual inspections of the transfer vehicle prior to use. This will ensure that any significant leaks are detected. Vehicle speed will be limited to 10 km/h or 20 km/h, depending on the section of the NSDF site where the vehicle is travelling. This will reduce the likelihood of a collision with other vehicles or objects leading to fire or container damage. Average accident frequency for heavy goods vehicles is 0.62 accidents per million km travelled [7-57]. Assuming an average distance of 1 km per transfer, this gives an annual frequency of 0.007 accidents/year. Taking into account low speed, additional vehicle check-ups and driver training for radioactive waste transfers, a safety factor of 10 can be included. Only a small proportion of all vehicle accidents result in a fire [7-57]: • Crash fires: 0.07% of all accidents. • Non-crash fires: 9.5% of all accidents. • Overturn accident initiating a fire: 0.6% of all accidents. Furthermore, no more than one in two fires would be an engulfing fire, and therefore, a conditional probability of two may be

Event	Screening Result and Rationale
	added to the fire ignition frequencies. This results in the total of 0.0003 transfer accidents per year, resulting in a fire engulfing radioactive waste. This value is above the SFL. If such an accident were to occur, it is possible that it would lead to environmental contamination due to dispersion of radioactive material. Therefore, a consequence assessment is required. Traffic along the waste transfer route may also lead to a collision with safety-related structures, e.g. with a standby generator, fuel storage building or leachate storage tanks. The transfer vehicle will be operated by an experienced driver and transportation barriers (such as bollards or staggered jersey barriers) will be installed around any safety-significant structures along the route to prevent a collision.
Construction accident resulting in personal injury	Consequence assessment not required (Pre-closure). Normal CNL governance and programs will apply. Canadian Nuclear Laboratories employee health and safety policy is defined by Occupational Safety and Health (OSH) program. This program ensures that a safe and healthy work environment is maintained at CNL facilities, minimizing losses associated with hazardous conditions, accidents and injuries in the workplace. The OSH program specifies the procedures, supporting documents, records and forms, and training needed to effectively realize the OSH objectives. This program complies with applicable Federal and Provincial occupational health and safety legislation, regulations and standards. The impact to workers during construction would be incurred through conventional hazards rather than radiological exposure. Potential impacts are addressed in the EIS on the basis of health and safety data from similar projects.
Criticality	Consequence assessment not required (Pre-closure). The CNSC Guidance for Nuclear Criticality Safety [7-58] defines how an adequate Upper Subcritical Limit should be determined. Quantities of fissile material disposed within the NSDF may exceed the guidance of Upper Subcritical Limit values provided in [7-58]. Therefore, criticality assessments are required for the operational period. These assessments would identify and evaluate potential abnormal conditions, such as high fissile inventory, inhomogeneity, improved moderation, flooding, over-stacking and migration during the post-closure phase.
Loss of shielding	Consequence assessment not required (Pre-closure). Waste packages transferred to the NSDF will be within the NSDF dose rate limits for contact- or remote – handling. There is a risk of human error resulting in inadequate packaging and worker dose. There is also a risk of loss of shielding due to failure of

Event	Screening Result and Rationale
	containers or structures. Special arrangements will be made for on-site transfer of any packages containing waste forms with high dose rates. Access controls will be used to mitigate onsite worker exposure, and an assessment will be completed to determine the remediation methodology for managing damaged packages. The frequency of this event has been evaluated as “Extremely Rare” based on the multiple years of experience of handling waste packages at the CRL site [7-59]. At this time of writing there is no design information on packaging and waste handling equipment; however radioactive waste handling is a routine operation and the NSDF design and operating procedures will ensure that the risk of such an event is minimized and that potential consequences are acceptable. Potential consequences of such an event are assessed in the SAR.
Flooding of ECM due to Underdrain clogging	Consequence assessment not required (Pre-closure). In accordance with design requirements, a separation of 1.5 m will be in place between the groundwater table and the HDPE geomembrane in the secondary base liner. A passive underdrain may be installed to ensure this gap is in place until cell closure, when a drawdown will result from interception of precipitation and recharge. If installed, such an underdrain may clog over time. If this were to occur during pre-closure or Institutional Control period, the resulting rise of the groundwater table and pressure head changes would be detected via monitoring. In this case, alternative means could be put into place. Such active measures would not be possible after the end of the Institutional Control. Clogging of the underdrain would lead to a rise of the groundwater table, which, although unlikely, could in turn lead to failure of the base liner due to hydrostatic pressure and uplift and flooding of the ECM cells. This scenario is addressed by ensuring that the ECM is designed so that separation from the groundwater is assured during post-closure without reliance on the underdrain.

Overall, 13 external and 15 internal hazard categories with potential radiological consequences have been reviewed. It was determined that the following bounding accident scenarios cannot be screened out, and therefore, require a consequence assessment.

1. Earthquakes (pre-closure).

An assessment is required to evaluate consequences of a seismic event that may damage the berms and engineered cover of the ECM, resulting in infiltration of water into the waste and penetration of contaminated leachate into the groundwater.

Consequence assessment is described in Section 8.6.3.

2. Lightning and forest fires (pre-closure).

An assessment is required to evaluate consequences of a fire in the temporary waste accumulation areas, leading to ignition of temporary stored waste and radionuclide dispersion. Lightning has been grouped together with fires because lightning is an initiating event that would potentially result in a fire.

Consequence assessment is described in Section 7.4.3.

3. On-site transfer accident (pre-closure).

An assessment is required to evaluate consequences of scenarios involving damage to radioactive waste packages during on-site transfers. This includes fire-related accident variants, and, non-fire (i.e. breach) accident variants.

Consequence assessment is described in Section 7.4.3.

4. Criticality (pre- and post-closure).

Criticality analysis is required to demonstrate that the scenario can be excluded due to low quantity of fissile material and/or design features of the NSDF.

This is provided in the SAR as described in Section 7.5.

7.4.3 Accident Consequence Assessment

This section provides an assessment of doses to human receptors resulting from the postulated bounding accidents during the pre-closure phase. The analysis is based on the proposed transportation and temporary storage arrangements [7-52] and bounding accident scenarios which were identified as requiring a consequence assessment in Section 7.4.2. It was determined that the following bounding accident scenarios with potential radiological consequences cannot be screened out, and therefore, require consequence assessments:

- On-site waste transfer accident due to a vehicle fire, engulfing radioactive material.
- Lightning and forest fires resulting in the fire impacting radioactive waste in temporary storage areas.

7.4.3.1 Description of Accident Scenarios

For the on-site transfer accident, the following three accident scenarios are investigated:

1. Fire during on-site transfer:

   A transportation vehicle, transferring 10 radioactive waste packages is involved in the postulated fire accident. The fire will last for one hour before any mitigation measures are taken.

2. Breach of waste packages due to low energy impact on the waste package during transportation on-site:

   The accident considered represents low energy impact on the waste package during on-site transfer. Loss of containment occurs as the result of the accident, with 10 packages of waste being involved with inventory defined in Table 4-3. It is assumed the radionuclides will be released to the environment over a one-hour period during the postulated accident before any mitigation measures are taken.

3. The third scenario considered is a fire (regardless of its initiating event) impacting radioactive waste located in temporary storage. It is important to note that – as mentioned in Section 5.2.2 – only bulk and packaged contact handleable waste meeting LLW limits will be suitable for temporary storage; higher-activity wastes (e.g. bunker wastes, non-contact-handleable wastes) will not be placed in temporary storage. From this, it is assumed that up to 590 m^3 of bulk waste and 90 m^3 of packaged contact-handleable waste (i.e. the maximum inventory of the temporary storage area; radionuclide concentrations as per Table 4-2) could be involved in the postulated fire accident in the temporary storage area. The fire is assumed to last for one hour before any mitigation measures are taken.

In addition to exposure to airborne emissions during the postulated package breach accident, NEWs could be exposed to direct gamma radiation due to loss of shielding. Although the design of non-contact handleable containers is not available at this time, it is expected that appropriate safety precautions will be assured for such items. Emergency procedures will ensure that the time spent at short distances is minimized and therefore, exposure duration will be minimized. External exposure is evaluated in the SAR. Dose to NEWs due to loss of shielding is a small fraction of dose resulting from airborne emissions.

7.4.3.2 Emission Estimate

Transfer Accidents:

In the case of accidents involving fire or breach of containers during transfer, container inventory corresponding to waste stored within bunkers was used in the analysis (see Table 4-3). Such wastes represent a small fraction of approximately 1% by volume of the total wastes that will be disposed of at the NSDF.

Temporary Storage Area - Fire Accident:

For the scenario involving fire in the temporary storage area, the radionuclide concentrations used are as follows:

- Bulk Waste: based on the reference radionuclide concentrations outlined in Table 4-2;
- Packaged (Contact-Handleable) Waste: based on the accidents radionuclide concentrations outlined in Table 4-3.

Note that higher activity waste streams – i.e. packaged *non*-contact-handleable wastes - will be disposed immediately after transfer to the NSDF rather than placed in temporary storage (see Section 5.2.2 for details).

Source Terms:

For a, given inventory, airborne emissions were calculated using the methodology described by U.S. DOE the U.S. DOE and IAEA methodology [7-60] and [7-61].

$$R = MAR \times DR \times ARF \times RF \times LPF$$

Where:

- R = Radioactivity released to air, Bq.
- MAR = Material at risk; the amount of radionuclides, in Bq, available to be acted on by the postulated accident.
- DR = Damage ratio; the fraction of the MAR impacted by the accident-generated conditions.
- ARF = Airborne release fraction; the coefficient used to estimate the amount of a radioactive material suspended in air as an aerosol available for transport due to the postulated accident.
- RF = Respirable fraction; Fraction of the release in the form of respirable particles.
- LPF = Leak Path Factor; the fraction of the radionuclides in the aerosol transported through some confinement deposition or filtration mechanism.

The input parameters required to estimate airborne release following the accident are summarized in Table 7-9 and Table 7-10.

Table 7-9 Input Parameters for the Calculation of Airborne Emissions

Input parameter (Symbol)	Unit	Fire during transportation/ temporary storage	Container breach
Damage ratio (DR)	%	50%*	50% (assumed value)
Airborne release fraction (ARF)	Unitless	See Table 7-10	0.001 [7-61]
Respirable fraction(RF)**	Unitless	1	1 for HTO, Cl-36 and I-129 and 0.1 for all other radionuclides [7-61].
Leak Path factor(LPF)	Unitless	1	1

Note:

*It is assumed that during the transfer, the waste is packaged in a container which is steel-walled with lid. For bulk waste in temporary storage, it is assumed that no more than 50% of the waste material will be engulfed in fire with access to air.

**Respirable fraction represents the fraction of airborne particles that are in the respirable size range. This fraction is used for dose calculation due to inhalation only.

Table 7-10 Airborne Release Fraction during Fire Accident [7-60]

Radionuclides	Airborne release fraction
Ag-108m	0.01
Am-241	0.001
Am-243	0.001
C-14	0.01
Cl-36	0.5
Co-60	0.001
Cs-135	0.01
Cs-137	0.01
H-3	0.5
I-129	0.5
Mo-93	0.01
Nb-94	0.01
Ni-59	0.01
Ni-63	0.01
Np-237	0.001
Pu-239	0.001
Pu-240	0.001
Pu-241	0.001
Pu-242	0.001

Radionuclides	Airborne release fraction
Ra-226	0.001
Se-79	0.01
Sn-126	0.01
Sr-90	0.01
Tc-99	0.01
Th-232	0.001
U-233	0.001
U-234	0.001
U-235	0.001
U-238	0.001
Zr-93	0.01

7.4.3.3 Selection of Human Receptors

Doses to humans resulting from the postulated accidents are estimated for the following two types of receptors:

- Drivers and other on-site NEWs.
- Off-site public, consisting of three age classes (infant, child and adult).

In the event of a fire or container breach, these receptors will be exposed to the radionuclide releases resulting from the accident through inhalation and immersion. Additionally, the off-site public will also be exposed to the contaminated soil due to the deposition of airborne emissions.

It is assumed that following a fire or container breach accident, the workers (drivers) will be exposed for five minutes prior to evacuation or use of protective equipment. It is also assumed there will be non-NEWs present on-site when the accident occurs. The nearest public receptors are assumed to be located 3,000 m away from the scene, which is the distance from the proposed NSDF to cottage resident described in CNL's DRL report [7-62]. These receptors will be exposed to the releases for one hour for inhalation and immersion and one month to contaminated soil. The above assumptions are summarized in Table 7-11.

Table 7-11 Receptors and Assumed Exposure Times and Distances from the Waste Involved in the Postulated Accident

Receptor	Exposure time	Distance
NEWs	Five minutes	At accident site
Member of the public	One hour for inhalation and immersion; 30 days for exposure to contaminated soil (as per N288.2-12 [7-63]).	3,000 m

Note: see Section 3.2 for receptor locations.

7.4.3.4 Calculation of Air Concentrations at Different Receptor Locations

With regards to terrain, Chalk River site does not fall under the definition of “complex terrain” in accordance with CSA N288.2-14 [7-63]. Clause 6.4.2.2 of [7-63] defines a number of features characterizing complex terrains, such as slopes, mountains, valley winds, etc. These features are not present at the NSDF site and between NSDF site and Potential Critical Group locations.

<u>Calculating Air Concentrations for NEWs – Transfer Accident Scenarios:</u>

For transfer accident scenarios, the air concentration in the immediate vicinity where NEWs are located is calculated based on the following equation:

$$C_{WO} = R / V_{AIR}$$

Where:

C_{WO} = Air Concentration near Workers, Bq/m^3

R = Radioactivity released to air, Bq

V_{AIR}= Volume of Air, m^3 [see Table 7-12]

<u>Calculating Air Concentrations for NEWs – Temporary Storage Area Fire Scenario:</u>

For the temporary storage area fire scenario, a two-zone box model approach is used based on [7-64]. In the two-zone box model, a receiving volume is considered to contain two zones – a near field zone surrounding the emission source, and a far-field zone comprising the remainder of the receiving volume. The air in each zone is completely mixed but with a limited air exchange between the two zones. The radius of the hemisphere is selected to contain the breathing zone of the worker (i.e. 2 m height). The flow (β) into and out of the near field is calculated as a rate in m^3/s. The receiving volume supply and exhaust air flow (F) is also calculated as a rate in m^3/s. For a source term emission rate of ‘QR’ (in Bq/s), the concentrations in near field (C_{NF}) and far field (C_{FF}) are calculated as follows:

$$C_{NF} = QR/F + QR/\beta \qquad \text{(in Bq/m}^3\text{ or g/m}^3\text{)}$$

$$C_{FF} = QR/F \qquad \text{(in Bq/m}^3\text{ or g/m}^3\text{)}$$

The value of β is calculated using the values of the near field radius (R) in meters, receiving volume (V_{AIR}) in m^3, and F as follows:

$$\beta = 0.48\ F \times V_{AIR} / R^3$$

Where,

B = flow between near-field and far-field (in m^3/s)

F = air supply/ventilation flow (in m^3/s) [255 m^3/s; calculated as windspeed (see Table 7-12), multiplied by, the cross-sectional area of the 600 m^3 air volume (V_{AIR}) (see Table 7-12)]

V_{AIR} = total receiving air volume (in m^3) [assumed to be equal to 600 m^3, see Table 7-12]

R = chosen near-field radius (in m) [i.e. assumed breathing height, 2 m]

Calculating Air Concentrations for Public – Transfer Accidents *and* Temporary Storage Area Fire Accident:

The following equation was used to estimate the concentration of the radionuclides in air at the off-site locations [7-60]

$$C_{a,I} = Q_i \times DF_m / \bar{u}$$

Where:

$C_{a,i}$ = Concentration of the radionuclide i in air, Bq/m^3

Q_i = Release rate of radionuclide i, Bq/s

$\bar{u}$ = Average wind speed, m/s

DF_m = Dilution factor, m^{-2}

The values of parameters which are required to estimate air concentrations following the accident, are summarized in Table 7-12.

Table 7-12 Parameters for the Calculation of Air Concentrations

Input parameters (Symbol)	Unit	Values	Note
Volume of air affected (receiving air volume) (V_{AIR})	m^3	600	A conservative value for a 5-minute Gaussian plume release [7-61].
Average wind speed ($\bar{u}$)	m/s	3.6	Annual average wind speed in Ottawa for the period of 1980 to 2010 [7-62].
Dilution factor at off-site location (DF_m)	m^{-2}	1.1E-4 (at distance of 3 000 m from the source)	Based on [7-60]. Stability Class F is conservatively assumed.

Calculation of Dose to Receptors

Once the concentrations of the radionuclides at the receptor locations were calculated, doses to receptors, taking into account different pathways as discussed before, are estimated as follows:

$$Dose\ (inh) = C_a \times IR \times T \times DC_i$$

$$Dose\ (imm) = C_a \times T \times DC_a$$

$$Dose\ (soil) = C_s \times T \times DC_g$$

$$Dose = Dose\ (inh) + Dose\ (imm) + Dose\ (soil)$$

Where

- Dose= Total dose from different pathways, Sv
- Dose (inh) = Dose due to inhalation, Sv
- Dose (imm) = Dose due to immersion in air, Sv
- Dose (soil) = Dose due to exposure to contaminated soil, Sv
- C_a= Concentration of the radionuclide in air, Bq/m^3
- C_s= Concentration of the radionuclide in soil, Bq/m^2
- IR= Inhalation rate, m^3/y
- T= Exposure time, s
- DC_i= Dose coefficient for inhalation, Sv/Bq
- DC_a= Dose coefficient for immersion in air, Sv/y per Bq/m^3
- DC_g= Dose coefficient for exposure to contaminated soil, Sv/y per Bq/m^2

The dose coefficients used to calculate dose to human receptors were obtained from CSA N288.1-14 [7-1], ICRP 119 (2012) [7-65], and Health Canada (1999) [7-66]. A higher inhalation rate for workers of 14,016 m^3/y was assumed [7-67].

7.4.3.5 Estimated Doses Resulting from Postulated Accidents

Doses to different receptors were calculated for each of the bonding scenarios and are compared to criteria for ‘extremely rare’ events, as defined in Section 2.

For the transfer accident scenario, the event frequency has been estimated to be 0.0003 overall (see Section 7.4.2). However, since “bunker wastes” represent much less than 10% of the inventory, the probability of this event occurring and also involving “bunker wastes” has been classified as “Extremely Rare”.

For the temporary storage area fire scenario, lightning strike frequencies (see Section 7.4.2) were estimated to be less than 0.01, with a further reduction to $<10^{-4}$ due to lightning protection measures that will be in place. Therefore, the resulting probability has been classified as “Extremely Rare”.

The results are presented in Table 7-13 through Table 7-15 .

Table 7-13 Dose to Human Receptors Resulting from On-site transfer fire

Receptors	Dose to receptors (mSv)	Dose Criteron[1]	Below Dose Criterion (Y/N)
NEWs	5.72E-01	50-100 mSv	Y
Public –Adult	3.29E-04	5-100 mSv	Y
Public -Child	3.51E-04	5-100 mSv	Y
Public –Infant	2.49E-04	5-100 mSv	Y

Note: 1 –See probability classification discussion above.

Table 7-14 Dose to Human Receptors Resulting from On-site transfer package breach

Receptors	Dose to receptors (mSv)	Dose Criteron[1]	Below Dose Criterion (Y/N)
NEWs	2.54E-01	50-100 mSv	Y
Public –Adult	5.56E-05	5-100 mSv	Y
Public -Child	5.64E-05	5-100 mSv	Y
Public –Infant	6.32E-05	5-100 mSv	Y

Note: 1 –See probability classification discussion above.

Table 7-15 Dose to Human Receptors Resulting from Fire during Temporary Storage

Receptors	Dose to receptors (mSv)	Dose Criteron[1]	Below Dose Criterion (Y/N)
NEWs[2]	1.68E+00	50-100 mSv	Y
Public –Adult	1.49E-01	5-100 mSv	Y
Public -Child	1.36E-01	5-100 mSv	Y
Public –Infant	5.27E-02	5-100 mSv	Y

Notes:

1 – See probability classification discussion above.

2 – Dose to NEWs calculated using near-field air concentration (C_{NF}) as the exposure concentration (C_a).

In all cases, the estimated doses to members of the public are below the respective dose acceptance criteria corresponding to Extremely Rare accidents (see Table 2-1).

Furthermore, for scenarios involving fire and breach of waste packages during transportation, doses to NEWs are approximately 1% of the 50 mSv annual dose limit for normal operations (see Section 2.2), and, doses to members of the public are less than 0.1% of the 1 mSv public dose limit for normal operations (see Section 2.1). Whereas for the fire accident during temporary storage, doses to NEWs are estimated to be approximately 3% of the 50 mSv annual dose limit for normal operations (see Section 2.2), and, doses to members of the public are approximately 15% of the 1mSv public dose limit for normal operations (see Section 2.1).

7.5 Criticality

A Criticality Safety Document will be produced to support detailed design for the project. This document will include the limits and restrictions related to criticality safety, as well as a criticality safety analysis demonstrating that the NSDF remains subcritical under normal and credible abnormal conditions.

The criticality safety analysis will establish upper subcritical limits (USLs) for fissionable material (FM) concentrations in waste and leachate at the NSDF in compliance with regulatory requirements [7-58]. These USLs will be used to establish limits on mass concentration of fissile material for the waste stored in the ECM. The USL values will be determined from calculational methods using the SCALE computer code, and from experimental values identified in ANSI/ANS 8.1 [7-68].

Potentially hazardous scenarios will be assessed for criticality by comparison with the USLs. For scenarios which exceed a USL, and where the estimated frequency of occurrence is greater than 10^{-6} per year, criticality safety controls will be established to reduce the risk to an acceptable level.

The actual criticality safety limits and restrictions for the NSDF will be provided as part of a detailed criticality safety analysis for the final design.

7.6 Uncertainties in Pre-Closure Analysis

Table 7-16 describes key uncertainties in assessing consequences from normal operational releases and how conservatism in the analysis and assumptions addressed these uncertainties.

Table 7-16 Uncertainties in Pre-Closure Assessment, Normal Operations

Parameter	Assessment Scenario	Uncertainty	Conservatism and assumptions
Inventory	All Scenarios	There is uncertainty with regards to the inventory of radionuclides that have been accumulated over the decades of operation at the CRL site. It is not known what wastes may be generated by future operations at the CRL site and by external consigners of radioactive wastes which may be disposed of at the NSDF.	• Both already accumulated wastes and those that will be generated in the future will have to meet the NSDF WAC as a control measure. • Estimates of the total ECM inventory were made conservatively using available data on wastes that are currently stored at CRL site. It is anticipated that the National Research Universal reactor will be shut down in 2018 and isotope production has already ended. Higher activity waste

Parameter	Assessment Scenario	Uncertainty	Conservatism and assumptions
			streams will no longer be generated once operations cease. Decommissioning and Environmental Remediation waste streams are associated which much lower levels of radioactivity.
Source term	Assessment of doses to members of the public.	Airborne and groundwater release rates.	• Waterborne releases from the WWTP are assumed to contain contaminants at maximum permissible concentrations. This is a bounding assumption; in most cases concentrations will be a small fraction of maximum permissible concentrations. • Airborne releases from the ECM are based on empirical data for C-14 and HTO and on a conservative model for Radon. The estimates neglect loss of contaminants over time, and decay as they migrate through the cover of capped cells.
Conceptual Model	Assessment of waterborne doses.	Contaminant transport in groundwater towards East Swamp Stream and then onwards to Perch Lake, Perch Creek and Ottawa River.	• Conservatively assumed instantaneous transfer of radionuclides towards receptor water bodies.
Assessment of doses to members of the public	Atmospheric and waterborne exposure pathways.	Modelling parameters.	• Conservative assumptions for dispersion and consumption rate parameters based on the DRL model for CNL site. Atmospheric dispersion and doses to the public are evaluated in accordance with CSA N288.1 [7-1], which provides a model based on conservative values for food, water, soil, and air intake rates

Parameter	Assessment Scenario	Uncertainty	Conservatism and assumptions
			for the representative person, typically at the 95th percentile level. Conservative values are also chosen for occupancy and other exposure factors. • Estimated doses represent a very small fraction of the limit.
Assessment of doses to non-human biota	Atmospheric and waterborne exposure pathways.	Modelling parameters.	• Conservative exposure parameters were used, consistent with the quantitative risk assessment methodology described in CSA N288.6 [7-2].
Assessment of radiological risks to populations of non-human biota	Normal operations, all pathways.	Variability in dose criteria among jurisdictions.	A screening level of 10 µGy/h should be considered as "below concern" based on generic screening calculations. If this level is exceeded, then a more detailed evaluation is required above such levels [7-69]. As such, this is a de minimus level, which is not meant to be a limiting criterion. Benchmarks selected for this assessment are consistent with Canadian ERA [7-2]. They are appropriate for the site-specific quantitative ecological risk assessment conducted for the NSDF.
Worker doses	External and internal exposure	Worker doses cannot be estimated at this time, given lack of detailed design information on operations, shielding and equipment.	• Worker doses will comply with regulatory limits and be ALARA in compliance with CRL's governance as all of the considered waste streams are routinely handled by CNL. An indication of the expected doses is provided in Section 7.1.2 based on CNL's experience. Further information on CNL's RP

Parameter	Assessment Scenario	Uncertainty	Conservatism and assumptions
			is provided in Section 9. • Detailed Safety Analysis for the final design is presented in the SAR.

Table 7-17 describes key uncertainties in assessing consequences of accident scenarios and how conservatism in the analysis and assumptions addressed these uncertainties.

Table 7-17 Uncertainties in Pre-Closure Accident Analysis

Parameter	Accident Scenario	Uncertainty	Conservatism and assumptions
Inventory	Fire during on-site transfer. Fire during temporary storage of waste. Container breach.	Activities of radionuclides engulfed in fire.	• For on-site transfer and container breach, the assumed concentrations are based on the inventory of radioactive waste contained within bunkers, which is significantly higher than for most ECM waste streams. • For temporary storage, the inventory is represented using average concentrations even though only low activity soil remediation waste is likely to be in temporary storage at the NSDF site.
Accident source term	Fire during on-site transfer. Fire during temporary storage of waste.	Airborne release rates.	• Assumed a large fire, fully engulfing waste packages. • Used conservative values for key release parameters (ARF, RF and DR).
Air concentrations	Fire during on-site transfer. Fire during temporary storage of	Dispersion in air following and accident.	• Concentrations were estimated using conservative assumptions, such as low windspeed (minimizes dispersion and dilution of radionuclides), assumption that workers are directly in the plume near the source and a

Parameter	Accident Scenario	Uncertainty	Conservatism and assumptions
	waste.		small dispersion volume.
Scenario uncertainty	All	Selection and characteristics of bounding scenarios – uncertainty from the final design not being available at the time of this analysis.	• Bounding scenarios were determined based on the information available at the time of this analysis. Where the design information or other parameters have changed from the production of the PA up to final design where necessary the relevant models are re-analysed and documented in the SAR. Ultimately, the feasibility of ensuring that such operations can be conducted safely is assured through compliance with CRL's internal governance. This is because all of the considered waste streams are routinely handled by CNL, and therefore fall within operational experience. Further information is provided in Section 9.

7.7 References

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8. POST-CLOSURE PERFORMANCE ASSESSMENT

This section summarized the assessment of the facility after the closure of the NSDF in the year 2100. It includes analysis of potential radiological consequences for a range of scenarios, including normal evolution of the system, and, select disruptive events (described further in Section 8.2.2).

Normal Evolution

Consequences for human receptors and non-human biota are provided for the Normal Evolution scenario. This scenario represents expected evolution of the ECM and the resulting releases based on conservative assumptions about the failure of the engineered barriers after the end of Institutional Control.

The following scenarios have been considered for normal evolution:

- Normal Evolution – Leaching Through the Liner Section 8.5.2.1
- Normal Evolution – Bathtub Section 8.5.2.2
- Normal Sensitivity Case 1 – Drinking water from Perch Creek Section 8.8.1.1
- Normal Sensitivity Case 2 – Living Close to the NSDF Section 8.8.1.2
- Normal Sensitivity Case 3 – Lower Distribution Coefficients Section 8.8.1.3
- Normal Sensitivity Case 4 – Dust from Dried Perch Creek Bed Section 8.8.1.4

Disruptive/Alternative Scenarios

Consequences are also considered for low probability “Disruptive” and “Alternative” scenarios that were identified for this period in Section 7.4.2 and in the FEPs analysis [8-1]. These include:

- **Inadvertent Human intrusion (H.I.)** scenarios, acute exposure of workers involved in drilling of an industrial well and chronic exposure of a farmer who places his house on top of the ECM while consuming contaminated vegetables and water.
- Exposure following **glaciation**, which may lead to erosion of the ECM and loss of containment.
- Exposure following a failure of the ECM due to a **seismic event**, which may result in a partial failure of the berms and cover and may lead to loss of some barriers.

Uncertainties are addressed via a combination of qualitative considerations, conservative assumptions, and sensitivity analyses (which examine the response to potential variations in scenarios and assumptions).

The following disruptive and alternative scenarios have been considered at year 2400:

- H.I. Main – Acute Section 8.6.1
- H.I. Main – Chronic Section 8.6.1
- H.I. Sensitivity Case 1 – Acute – Larger Diameter Well Section 8.8.2.1
- H.I. Sensitivity Case 2 – Chronic – 3 m Basement above ECM Section 8.8.2.2
- Glaciation Event Section 8.6.2
- Seismic Event Section 8.6.3

Additionally, to assess the sensitivity of these cases to the time at which they occur, each case was also assessed assuming that institutional control failed, and the intrusion event occurred at year 2200, and 2300, before the predicted end of institutional controls in year 2400. The scenarios are as follows:

- Time Sensitivity Case 1 – H.I. Main – Acute Section 8.8.3.1
- Time Sensitivity Case 2 – H.I. Main – Chronic Section 8.8.3.2
- Time Sensitivity Case 3 – Larger Diameter Well Section 8.8.3.3
- Time Sensitivity Case 4 –3 m Basement above ECM Section 8.8.3.3

8.1 Assessment Approach

The overall approach to the post-closure PA is consistent with guidance provided in G-320 [8-2]. The approach uses pathway analysis based on scenarios of expected evolution to evaluate potential:

1. Contaminant release from the ECM into the groundwater or atmosphere.
2. Contaminant transport in groundwater, surface water and air dispersion.
3. Transfer of radionuclides in the biosphere and receptor exposure.
4. Potential effects resulting from the exposure.

These key steps, as well as inputs and interfaces, relating to the post-closure PA, are presented in Figure 8-1.

The strategy used to demonstrate long-term safety includes scoping, bounding and conservative assessments used to illustrate the factors that are important to long-term safety and the limits of potential exposure. Deterministic calculations are augmented by sensitivity analysis to evaluate the response of model predictions to both conceptual and parameter variations.

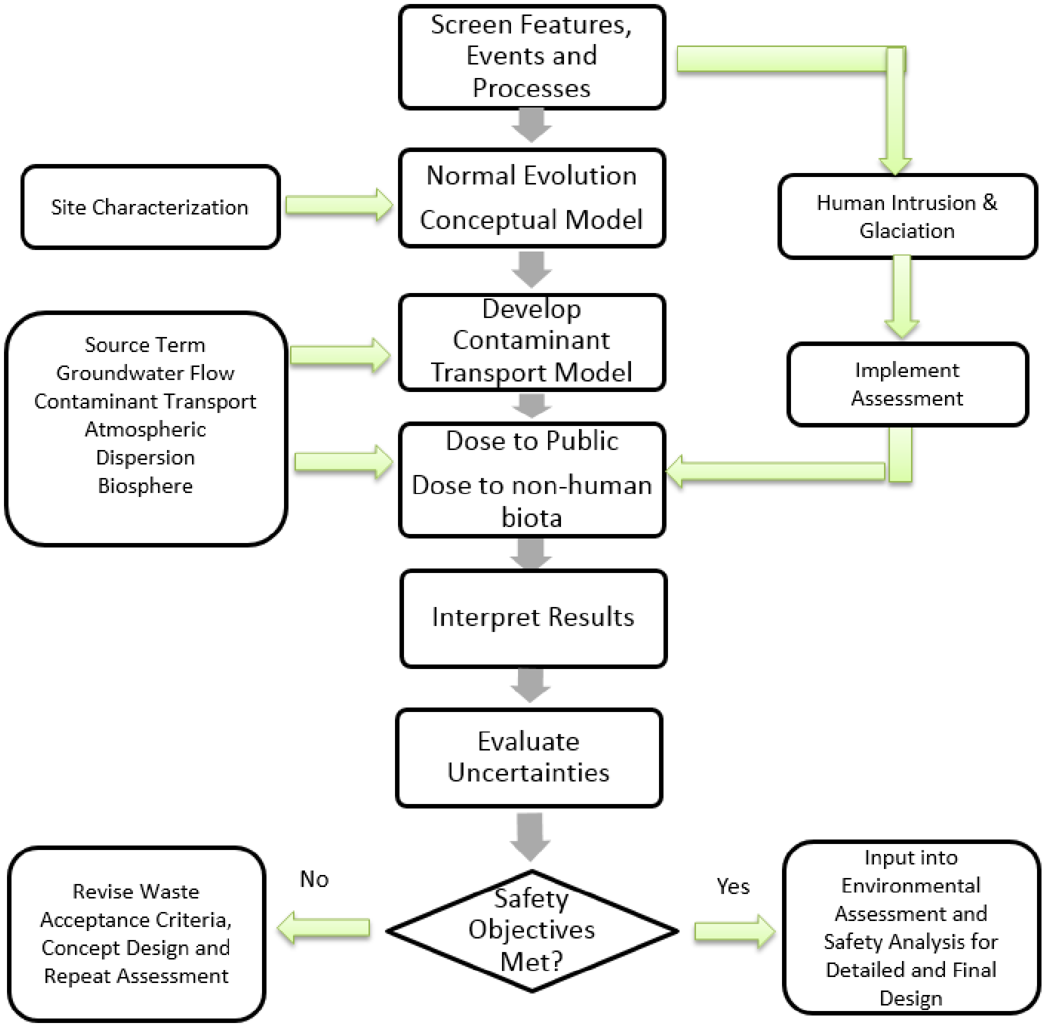

Figure 8-1 Post-Closure Performance Assessment Approach

Conservatism in the analysis is based on the following key assumptions:

1. Inventory was developed using data from the waste streams that are currently in storage at CRL. The vast majority of these stored waste streams have been generated as a result of operations at CRL and its predecessors. The majority of future wastes will be generated as a result of environmental remediation and decommissioning, which is associated with significantly lower radionuclide concentrations. Environmental remediation and decommissioning waste will dominate the total inventory of waste *by volume*, representing over 85% of the total, but will only account for a small portion of the total activity. Therefore, representing the entire volume of waste as high activity operational (stored) waste is conservative.
2. No credit has been taken for containers or waste conditioning beyond the period of Institutional Control. Furthermore, it was assumed that none of the inventory will have

leached out of the system prior to the year 2400. This ensures the most conservative estimates for the source term, only having been changed by the decay and ingrowth of the waste.

Contaminant transport in the groundwater was calibrated against site specific data [8-3], measured recharge and flow rates and known travel times for radionuclides based on historical and current data from monitoring of adjacent facilities. Current habits and consumption rates were assumed for PCG during post-closure under the Normal Evolution scenario (see Section 3.1.4) and are consistent with assumptions for the pre-closure period, as discussed in Section 3.1.2. Sensitivity analysis demonstrated that even increased local food consumption fractions and use of water in the outfall from Perch Creek for drinking, would not lead to exceedance of Safety Criteria by members of the public.

The long-term safety of the NSDF disposal concept is demonstrated by directly comparing predictions with Safety Criteria defined in Section 2.

8.2 Performance at Various Timeframes

8.2.1 Performance Prior to the end of Institutional Control

After the closure of all cells and following the decommissioning work, but prior to the end of the Institutional Control period (assumed to take place in the year 2400, except for the sensitivity analyses for inadvertent intrusion occurring at year 2200 and 2300, a conservative assumption), both the liner and the engineered cover of the ECM will be within their 550-year design life. See the discussion of timeframes in Section 5.

A small quantity of leachate will continue to be generated for a relatively short period of time after installation of engineered covers over all ECM disposal cells. The WWTP will continue to operate for as long as contaminated leachate is being generated.

Eventually, the level of moisture in the waste will reduce as all infiltration will be intercepted through evapotranspiration and drainage in the engineered cover. At that time, there will no longer be a need to operate the WWTP, which will be decommissioned. Any precipitation will be diverted to run-off so that following the closure of the ECM, the waste will remain dry throughout the Institutional Control period.

Active Institutional Control may involve monitoring, surveillance and remedial work. During the active Institutional Control period, the performance of the containment system will be monitored and the system will be maintained. Therefore, its functionality will be assured in accordance with design.

Ultimately monitoring during the active Institutional Control period will confirm when the facility can be released from active to passive Institutional Control, which involves restrictions of how the land can be used. As such, access to the site will continue to be controlled through the passive Institutional Control period. Site operators will maintain capability to remediate any deficiencies in vegetative cover or address issues with performance that may result from low probability beyond design basis events.

Therefore, there will be no contaminated liquid effluent emanating from the NSDF at that time. While minor fugitive emissions to air will continue, they will be bounded by emissions during operations, which were evaluated in Section 7.2.

The site will remain under passive Institutional Control for an extended period of time which would prevent drilling, excavation or taking up residence on top of the ECM.

8.2.2 Performance Following the End of Institutional Control

In all likelihood, the Institutional Control will continue beyond the year 2400. However, for the purposes of this assessment it has been assumed that all controls, including limitations on land use, cease in 2400, that the laws are no longer effective and that all societal memory of the facility will fade.

This will ultimately lead to the deterioration in the performance of engineered features of the ECM due to the effects of the environment on the engineered cover, base liner and other components of the containment. This will in turn lead to radionuclide leaching into the environment and may lead to exposure of members of the public. Such scenarios are considered as “Normal Evolution” in Section 8.4.

Following the institutional control, there is a small probability that members of the public will engage in inadvertent disruptive activities, such as drilling into the ECM or establishing a residence at the site. Human intrusion is a special case; both acute and chronic scenarios are considered in Section 8.6.1.

The next glaciation cycle is not predicted to begin for at least 100,000 years [8-4]. This may lead to erosion of the mound thereby, degrading the containment provided by the ECM. Earthquakes may also occur over extended periods of time and it is plausible that a beyond design event may take place after the end of Institutional Control, when it is no longer possible to mitigate the damage to the ECM’s structure. These “Alternative” scenarios, though considered to be extremely rare, are evaluated in Sections 8.6.2 and 8.6.3.

A number of additional simulations have been conducted to evaluate both scenario and parameter uncertainties. These are summarized in Section 8.8.

The combination of these scenarios and analyses was designed to replicate plausible FEPs that apply to post-closure, as per Section 8.3 [8-1].

8.3 Features, Events and Processes

Scenarios were developed based on the Features, Events and Processes, which have been screened as relevant to the post-closure phase of the project [8-1]. Each FEPs, defined as applicable to post-closure analysis for the NSDF project, is considered in Appendix A. Table 8-1 illustrates a few examples from this Appendix. This Appendix specifies how each FEPs is addressed within the current analysis.

Table 8-1 Events with Potential Radiological Consequences – External Events

FEP # and Title	FEP Description	Relevant Scenario(s)	How is FEP addressed
1. Assessment Basis			
0.01 Impacts of Concern	The long-term human health and environmental effects or risks that may arise from the disposed wastes and repository. These FEP include human health or environmental effects of concern in an assessment what effect and to whom/what), and human health or environmental effects ruled to be of no concern.	All post-closure scenarios	Radiological doses to humans and environmental effects will be considered for each scenario.
0.02 Timescales of Concern	Timescales of concern are the time periods over which the disposed wastes and repository may present some significant human health or environmental hazard.	All post-closure scenarios	All assessments capture peak exposures under each scenario.
0.03 Spatial Domain	The spatial domain of concern is the domain over which the disposed wastes and repository may present some significant human health or environmental hazard.	All post-closure scenarios	All assessments consider domain over which potential radiological impacts on humans and ecology are plausible, either via atmospheric dispersion or ground-surface water flow.
0.04 Repository Assumptions	Repository assumptions are the assumptions that are made in the assessment about the construction, operation, closure, and administration of the repository.	All post-closure scenarios	All assumptions are specified, justified and documented.
0.05 Future Human Action Assumptions	The assumptions made in the safety assessment concerning general boundary conditions for assessing future human action.	All post-closure scenarios.	Human Intrusion scenarios considered, including chronic and acute exposure.

Please find the full table in Appendix A.

8.4 Key Assessment Parameters

Doses to members of the public and to non-human biota during post-closure period were calculated based on the following parameters and assumptions:

- The ECM has a footprint of 285 m by 350 m with the maximum depth of stored waste of 13.83 m [8-5].
- The net infiltration rate through the ECM is 0.3 m/y, assuming a complete failure of the multi-layered engineered cover [8-5].
- Effective porosity of the saturated zone is 0.3 with the hydraulic conductivity of 5 360 m/y and hydraulic gradient of 0.007 m. The depth of the aquifer contributing to Perch Creek is 3 m. These parameters were derived based on site-specific parameters and adjusted by calibration to align with site-specific measurements and groundwater modelling results [8-3].
- The longitudinal dispersivity of the saturated zone is 0.3 m [8-6]. No lateral dispersion is assumed. The latter is a conservative assumption reflecting a relatively short transport route to Perch Creek.
- The site-specific distribution coefficients are used for aquifer and sediment (see Table 3-5). Standard values are used for representing retardation within the ECM [8-7].
- No credit is taken for the loss of inventory due to the release occurring prior to the end of Institutional Control. This is a conservative approach, maximizing the inventory available for leaching.
- The flow rate in Perch Creek is 1.77E6 m^3/y (5-year average) [8-6] and [8-8].
- Future climate, hydrological and hydrogeological conditions are the same as at present time.
- Human habits, specifically local food and water consumptions, are unchanged from the current conditions as defined by the site-specific lifestyle survey [8-9].

8.4.1 Radionuclide Activity

The activities of radionuclides in the ECM, and in the bunker waste, which is used to represent a specific, high activity, waste stream, were estimated using the RESRAD OFFSITE 3.1 code, based on the NSDF inventory (see Section 4.2). The inventories were calculated for the year 2400, taking into account only decay and ingrowth.

8.4.1.1 Reference Radionuclide Activity in the ECM (Total Inventory)

The estimated activities for the waste in the ECM, referred to as “Total Waste” are presented in Table 8-2. This waste was based on the reference inventory as presented in Table 4-2.

Table 8-2 Total Waste Inventory

Radionuclides	Activity in year 2200 (Bq/g)	Activity in year 2300 (Bq/g)	Activity in year 2400 (Bq/g) Base Case
Ac-227	3.77E-04	6.30E-04	8.82E-04
Ag-108m	3.67E-02	2.13E-02	1.23E-02
Am-241	1.88E+01	1.60E+01	1.37E+01
Am-243	9.36E-03	9.27E-03	9.19E-03
C-14	2.08E+01	2.06E+01	2.03E+01
Cl-36	9.32E-02	9.31E-02	9.31E-02
Co-60[1]	7.98E-05	1.55E-10	3.02E-16
Cs-135	3.20E-03	3.20E-03	3.20E-03
Cs-137	4.02E+03	3.98E+02	3.95E+01
H-3[1]	1.58E+00	5.77E-03	2.11E-05
I-129	7.15E-01	7.15E-01	7.15E-01
Mo-93	1.64E-05	1.61E-05	1.58E-05
Nb-93m	5.70E+00	5.70E+00	5.70E+00
Nb-94	1.42E+01	1.42E+01	1.41E+01
Ni-59	3.23E-02	3.22E-02	3.22E-02
Ni-63	3.33E+00	1.62E+00	7.85E-01
Np-237	2.99E-03	3.55E-03	4.03E-03
Pa-231	4.56E-04	7.09E-04	9.61E-04
Pb-210	2.62E-01	2.52E-01	2.41E-01
Po-210	2.62E-01	2.52E-01	2.41E-01
Pu-239	9.66E-01	9.63E-01	9.61E-01
Pu-240	1.48E+00	1.47E+00	1.45E+00
Pu-241	8.51E-06	6.91E-08	5.61E-10
Pu-242	4.53E-03	4.53E-03	4.53E-03
Ra-226	2.59E-01	2.48E-01	2.38E-01
Ra-228	1.05E+00	1.05E+00	1.05E+00
Se-79	1.04E-03	1.04E-03	1.04E-03
Sn-126	1.53E-03	1.53E-03	1.53E-03
Sr-90	1.11E+01	1.02E+00	9.46E-02
Tc-99	3.32E+00	3.32E+00	3.32E+00
Th-228	1.05E+00	1.05E+00	1.05E+00
Th-229	1.53E-04	2.37E-04	3.20E-04
Th-230	3.01E-03	4.69E-03	6.36E-03
Th-232	1.05E+00	1.05E+00	1.05E+00
U-233	9.08E-03	9.07E-03	9.07E-03
U-234	1.86E+00	1.86E+00	1.86E+00

Radionuclides	Activity in year 2200 (Bq/g)	Activity in year 2300 (Bq/g)	Activity in year 2400 (Bq/g) Base Case
U-235	1.20E-01	1.20E-01	1.20E-01
U-236	7.97E-06	1.23E-05	1.67E-05
U-238	5.99E+00	5.99E+00	5.99E+00
Zr-93	5.70E+00	5.70E+00	5.70E+00

1 – Note that the activities used for Co-60 and H-3 are decayed by 50 years less than the other nuclides (i.e. 2350 used for the 2400 inventory, 2150 used for the 2200 inventory). This is done due to the short half lives of these isotopes, and is a conservative approximation, as it results in larger quantities of these isotopes being present. This assumption conservatively assumes that all Co-60 and H-3 are emplaced at the end of the operational timeframe (2070).

8.4.1.2 Reference Radionuclide Activity for Bunker Waste

The estimated activities for the Bunker Waste, which is used to represent a high activity waste stream, are presented in Table 8-3. This waste was based on the bunker waste inventory presented in Table 4-3, which is also the waste considered for accident scenarios (in the pre-closure assessment).

Table 8-3 Bunker Waste Inventory

Radionuclides	Activity in year 2200 (Bq/g)	Activity in year 2300 (Bq/g)	Activity in year 2400 (Bq/g) Base Case
Ac-227	1.10E-03	1.84E-03	2.57E-03
Ag-108m	4.76E-06	2.76E-06	1.60E-06
Am-241	8.62E+01	7.34E+01	6.25E+01
Am-243	2.06E-02	2.04E-02	2.02E-02
C-14	3.49E+01	3.45E+01	3.41E+01
Cl-36	1.27E-01	1.27E-01	1.27E-01
Co-60	1.92E-02	3.73E-08	7.26E-14
Cs-135	1.25E-02	1.25E-02	1.25E-02
Cs-137	2.91E+03	2.88E+02	2.86E+01
H-3	1.06E+03	3.86E+00	1.41E-02
I-129	3.40E+00	3.40E+00	3.40E+00
Mo-93	3.57E-05	3.50E-05	3.43E-05
Nb-93m	1.66E+01	1.66E+01	1.66E+01
Nb-94	5.93E+01	5.91E+01	5.89E+01
Ni-59	4.79E-02	4.79E-02	4.78E-02
Ni-63	1.00E+01	4.86E+00	2.36E+00
Np-237	1.34E-02	1.60E-02	1.82E-02
Pa-231	1.33E-03	2.07E-03	2.80E-03

Radionuclides	Activity in year 2200 (Bq/g)	Activity in year 2300 (Bq/g)	Activity in year 2400 (Bq/g) Base Case
Pb-210	1.00E+00	9.62E-01	9.22E-01
Po-210	1.00E+00	9.62E-01	9.22E-01
Pu-239	3.41E+00	3.40E+00	3.39E+00
Pu-240	5.10E+00	5.05E+00	5.00E+00
Pu-241	5.06E-03	4.11E-05	3.33E-07
Pu-242	1.85E-02	1.85E-02	1.85E-02
Ra-226	9.90E-01	9.49E-01	9.09E-01
Ra-228	4.97E+00	4.97E+00	4.97E+00
Se-79	3.32E-03	3.32E-03	3.32E-03
Sn-126	2.67E-03	2.67E-03	2.66E-03
Sr-90	4.92E+01	4.55E+00	4.21E-01
Tc-99	1.24E+00	1.24E+00	1.24E+00
Th-228	4.97E+00	4.97E+00	4.97E+00
Th-229	6.52E-04	1.01E-03	1.36E-03
Th-230	8.47E-03	1.32E-02	1.79E-02
Th-232	4.97E+00	4.97E+00	4.97E+00
U-233	3.87E-02	3.87E-02	3.87E-02
U-234	5.24E+00	5.24E+00	5.24E+00
U-235	3.50E-01	3.50E-01	3.50E-01
U-236	2.75E-05	4.25E-05	5.73E-05
U-238	1.44E+01	1.44E+01	1.44E+01
Zr-93	1.66E+01	1.66E+01	1.66E+01

8.5 Normal Evolution Scenarios

Over the following centuries, the vegetative cover over the ECM will be replaced with plants that provide less efficient evapotranspiration, soil may begin to erode as a result of weathering and the engineered cover is expected to deteriorate. Eventually, it is assumed that the waste, having dried out during the post-closure period of Institutional Control, will rehydrate and become partially saturated due to infiltration of precipitation (see Figure 1-5). At this time, one of two plausible scenarios may take place:

1. ***Leaching Through the Base Liner.***

   If the base liner fail at this time, then it will provide a pathway for the leachate into the groundwater. The radioactivity will be released as a result of sorption/desorption and in reality will be subject to solubility of specific elements. The resulting leachate will be transported via groundwater towards Perch Creek, from where it will be released into the Ottawa River.

2. ***Bathtub Effect Overflow Scenario.***

   If the base liner remains intact, then the infiltrating water will continue to be constrained by the ECM liner and berms. Depending on the rate of infiltration through the partially eroded cover, the ECM will be filled in with water. The waste will become fully saturated and within confines of the berms, the ECM will be fully filled with water and overflow to the surface grade at the lowest point of the berm. Depending on the rate of infiltration, the resulting overtopping leachate may transfer to Perch Creek via ground or surface water.

The design life of the ECM including the cover is 550 years. Nevertheless, a conservative assumption was made that the cover erodes and one of these scenarios may occur immediately following the end of Institutional Control, which is assumed to take place in year 2400. Were this scenario to occur at 2100, after closure, it would be detected as part of active Institutional Controls.

Both of these release scenarios will give rise to a potential transfer of radionuclides in the biosphere and potential exposure of members of the public. They are considered to be "Normal Evolution" scenarios. For the purposes of this assessment, it is assumed that the surrounding environment and population will maintain present characteristics as they relate to the spread of contaminants and potential exposure. This is consistent with the guidance provided in CNSC Guide G-320 [8-2], which states that:

"A normal evolution scenario should be based on reasonable extrapolation of present day site features and receptor lifestyles. It should include expected evolution of the site and degradation of the waste disposal system (gradual or total loss of barrier function) as it ages. Evolution scenarios are not expected to include biological evolution of individual receptor species, which can be assumed to be static for the purposes of the safety assessment."

It should be noted that, considered Normal Evolution scenarios already account for a range of potential environmental disruptions, which may impact the disposal facility. For example, by conservatively assuming failure of the engineered cover immediately after the end of Institutional Control, these scenarios account for any potential damage that may be caused to the barriers as a result of accelerated erosion or cover failures from forest fires, floods or seismic activity.

The "Alternative Evolution" and "Disruptive" scenarios and variations in principal parameters and human habits are described in Section 8.6, including environmental changes and human behaviours which may further challenge the integrity of the ECM and enhance potential exposures. Certain disruptive scenarios could be expected over very long periods of time, amounting to thousands of years. For this reason, and to reflect the high level of uncertainty in the environmental parameters and human behaviours over the long-term, in this assessment designations of "Normal Evolution" vs. "Alternative" and "Disruptive" scenarios were not intended as a commentary on their likelihood. Rather, they were designed to encompass a range of plausible developments and to evaluate the NSDF's performance under a diverse set of challenging conditions.

8.5.1 Methodology

Radiological materials have the potential to be released to the environment after the closure of the NSDF. Consequently, this could result in the potential contamination of various media, including air, surface water, soil, sediment, groundwater, and vegetation. As discussed in Section 3, the groundwater flow was modeled using calibrated transport parameters [8-3]. The exposure pathways considered in this work, and the methodology to calculate doses to humans and non-human biota, are consistent with CSA N288.1-14 [8-7] and CSA N288.6-12 [8-10].

The computer code RESRAD OFFSITE Version 3. 1, was used to evaluate leaching of radionuclides through the base liner for the normal evolution main case. For the bathtub scenario, the flux of radionuclides to the surface water as a result of overflowing was estimated, as discussed further in Section 8.5.2.2. In both cases, IMPACT Version 5.5.1 was used to estimate doses to PCGs due to the exposure to radiological emissions (see Section 1.9.2). Where available, verified site-specific and design-specific parameters were used in the analysis. In other cases, generic parameters were used, as specified in the Canadian standards referenced above.

For both normal evolution scenarios, it was assumed that the same PCGs as those currently present, will continue to be present in the vicinity of the Chalk River site and maintain habits and local food consumption rates which are consistent with present time (see Section 3.1), as per G-320. A set of sensitivity analyses with variations in locations and habits of PCGs is provided in Section 8.8.1.

The same set of indicator species was used for the assessment of effects on non-human biota (see Section 3.9).

8.5.2 Results for Normal Evolution Cases

8.5.2.1 Leaching Through Base Liner, Air, and Surface Water Pathways

Under this scenario, the engineered cover of the ECM begins to erode. Assuming there is no monitoring and maintenance in place, the engineered cover will be permitted to deteriorate unabated. At the same time, it is assumed that the base liner system fails, including formation of preferential water paths in the compacted clay liner. As a result, precipitation is progressively infiltrating through the cover resulting in water ingress into the waste, contaminated leachate then enters the groundwater system through the failed base liner system (Figure 8-2, consistent with the inventories in Section 4.2, shows the predicted leaching rates for the main radionuclides and the total flux). Contaminants are then transported to Perch Creek via groundwater and eventually flow to the Ottawa River.

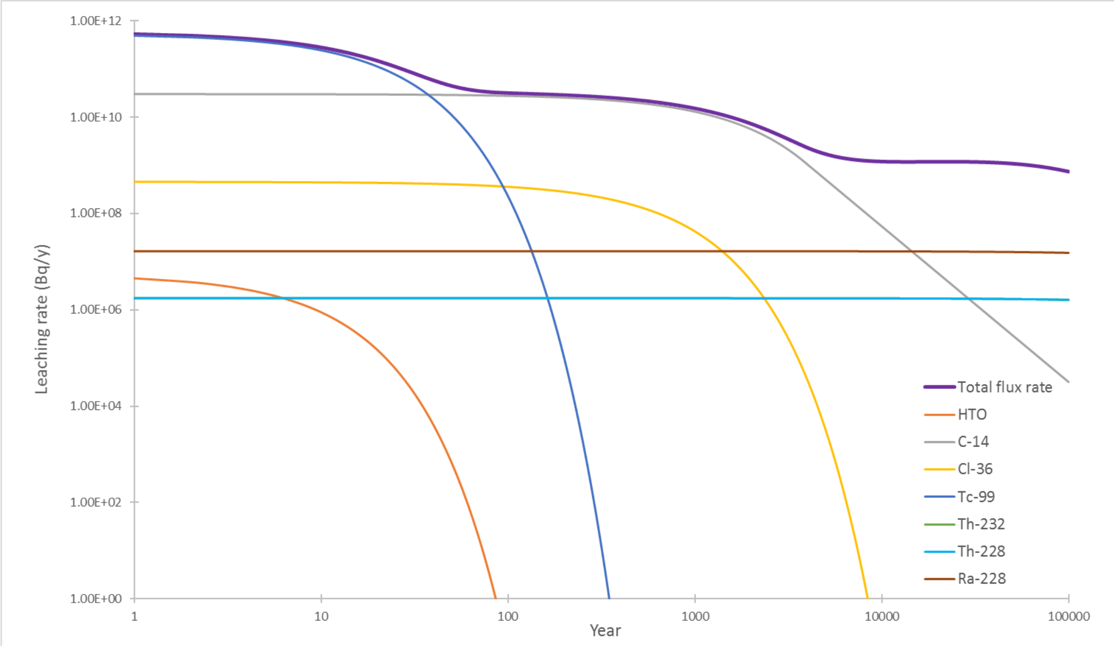

Figure 8-2 Predicted Leaching Rate, Years after the End of Institutional Control

Other exposure pathways that are ongoing while this leaching occurs include airborne pathways and surface water pathways.

Airborne radionuclides, such as tritium, C-14 and radon will continue to be emitted during the Post-closure period. However, the airborne emissions at these stages will be bounded by those prior to the closure of the NSDF. In particular, emissions of radon, will be reduced due to transport of gases through the ECM cover, resulting in significant decay prior to release into the environment. In addition, the inventory of tritium will be reduced due to leaching and radioactive decay during operations of the NSDF, while generation of carbon emissions will be reduced due to decomposition of organic substances during pre-closure and the resulting decrease in gas generation from organic material following the end of operations. As such, the impact of airborne emissions during post-closure will be bounded by operational releases (See Section 7.2), which result in doses of less than 0.01% of the limit and will not be evaluated further.

Waterborne emission rates from the ECM and contaminant transport into Perch Creek via groundwater were estimated using RESRAD OFFSITE. Biosphere modelling was conducted and doses to individual members of PCGs due to exposure to waterborne emissions from the NSDF were calculated using IMPACT 5.5.1. The results are presented in Table 8-4 and Figure 8-3. Additionally, Figure 8-4 shows the results on a log scale, compared to the dose constraint of 0.3 mSv/y. It can be seen that the doses are all well below the dose constraint. Figure 8-5 presents the percent contribution by radionuclide for the maximum dose to the most exposed receptor.

Table 8-4 Doses to PCGs during Post-Closure

Receptors	Dose to adult (mSv/y)	Dose to 10 year old Child (mSv/y)	Dose to one year old infant (mSv/y)
Cottager	6.7E-07	6.7E-07	7.3E-07
Pembroke	5.0E-05	9.0E-05	1.69E-04
Petawawa	4.7E-05	8.9E-05	1.67E-04
Laurentian Valley	4.6E-05	8.6E-05	1.68E-04

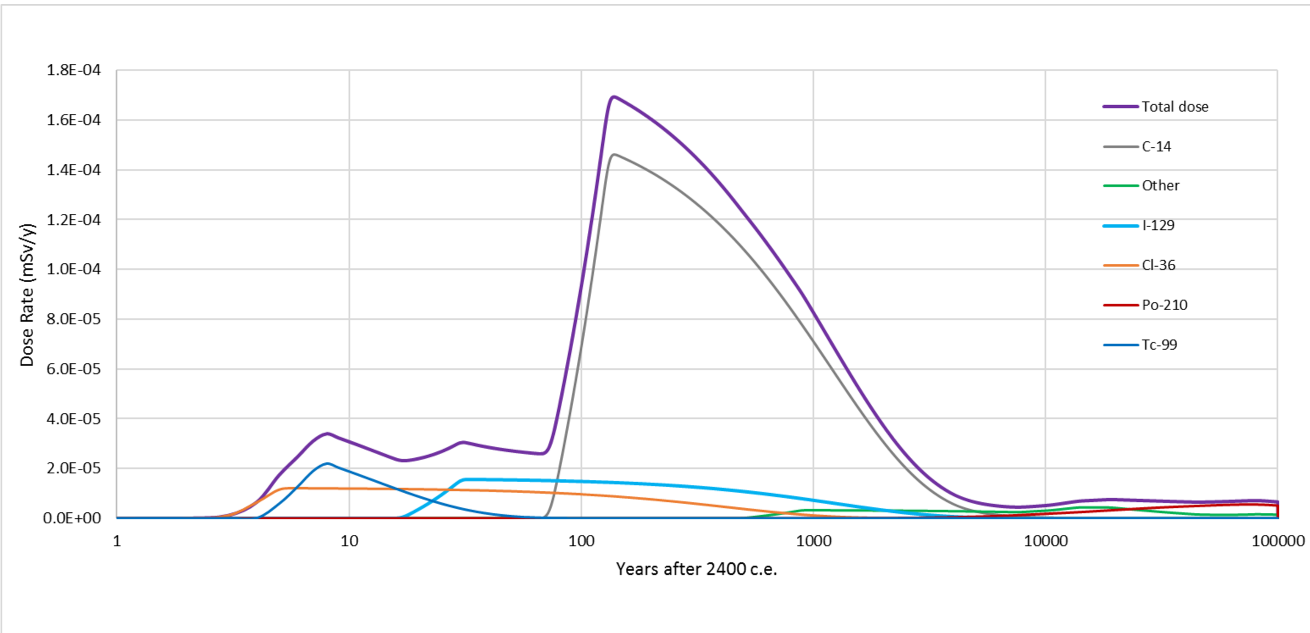

Figure 8-3 Predicted Dose to an Infant in Pembroke, years after the end of Institutional Control (Linear Scale)

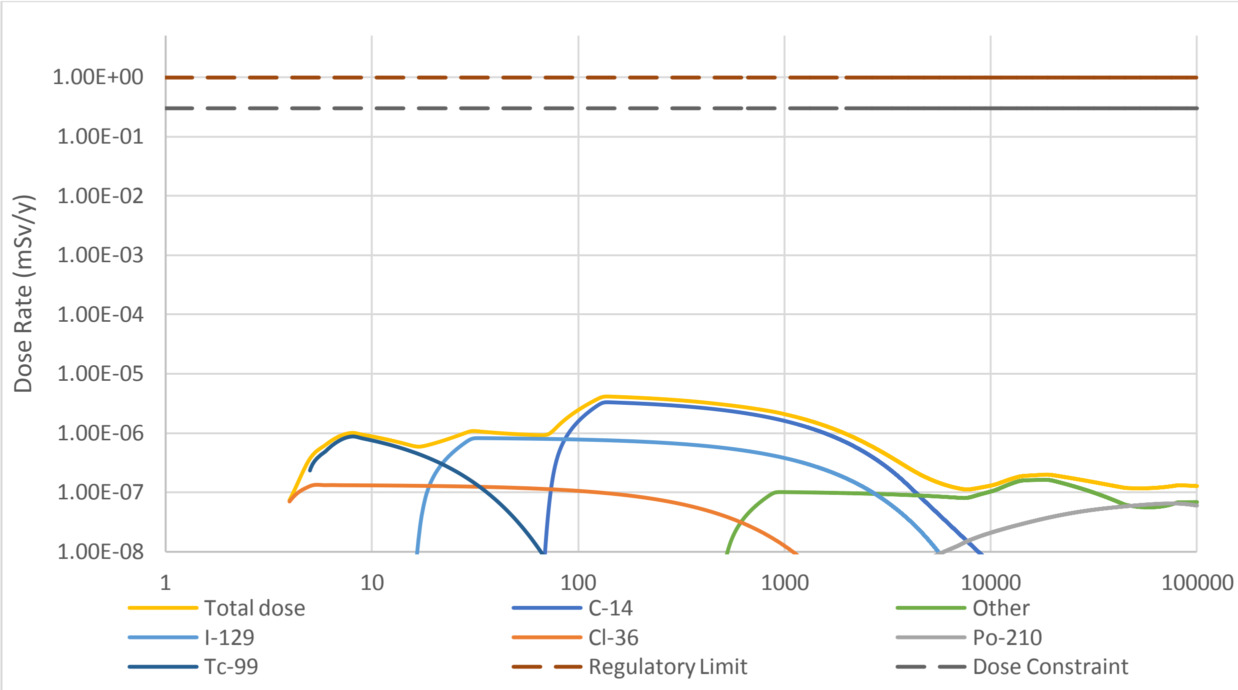

Figure 8-4 Predicted Dose to an Infant in Pembroke, years after the end of Institutional Control (Log Scale)

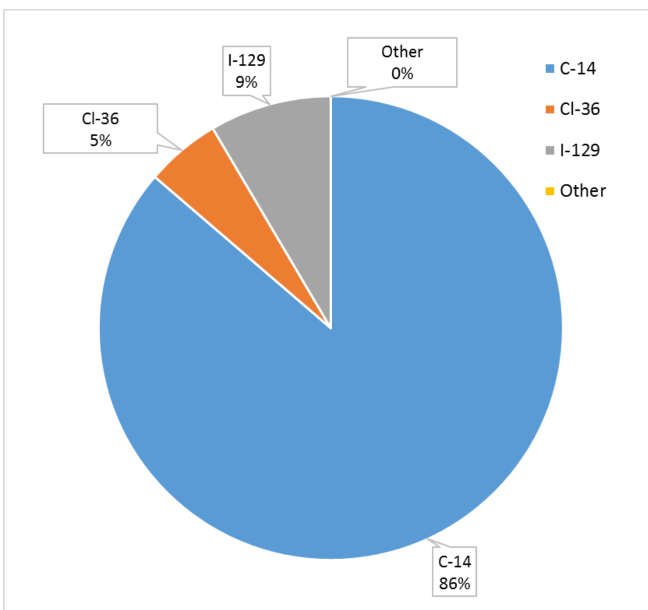

Figure 8-5 Percent Contribution by Radionuclide for Predicted Dose to an Infant in Pembroke

The maximum estimated dose to members of the critical group is 1.7E-4 mSv/y and 86% is from C-14. The peak is predicted to occur approximately 140 years after the end of Institutional Control and failure of the engineered cover. The critical group is represented by one year old infants in Pembroke. This amounts to 0.02% of the regulatory dose limit of 1 mSv/y and 0.06% of the dose constraint of 0.3 mSv/y. Doses to indicator species were calculated based on the methods specified in CSA N288.6-12 [8-10].

Table 8-5 Doses to Non-Human Biota

Taxa	Indicator	Dose due to waterborne emission (µGy/h)	Dose due to airborne emission (µGy/h)	Total dose (µGy/h)	Benchmark (µGy/h)	% of Benchmark
Aquatic Plant	Reed	1.3E+01	0.0E+00	1.33E+01	400	3.34%
Fish	Bluntnose minnow	8.9E+00	0.0E+00	8.86E+00	400	2.21%
	Black Bullhead	8.9E+00	0.0E+00	8.86E+00	400	2.21%
	Pike	8.9E+00	0.0E+00	8.86E+00	400	2.21%
Terrestrial Plant	Red Maple	0.0E+00	1.8E-03	1.80E-03	100	<0.01%
Insect	Monarch Butterfly	0.0E+00	1.7E-03	1.70E-03	100	<0.01%
Mammal	Little brown Myotis	1.7E-06	2.4E-03	2.40E-03	100	<0.01%
	Meadow Vole	5.0E-06	4.7E-04	4.75E-04	100	<0.01%
	White-tailed deer	5.3E-02	2.0E-03	5.53E-02	100	0.06%
	Short-tailed Shrew	3.4E-06	9.1E-04	9.13E-04	100	<0.01%
	Eastern Wolf	1.6E-01	4.0E-03	1.65E-01	100	0.16%
Reptile	Snapping Turtle	3.4E+00	0.0E+00	3.39E+00	100	3.39%
	Common Watersnake	3.4E+00	0.0E+00	3.39E+00	100	3.39%
	Eastern Milksnake	0.0E+00	7.5E-04	7.50E-04	100	<0.01%
Amphibian	Green Frog	3.4E+00	0.0E+00	3.39E+00	100	3.39%
Bird	Canada Warbler	2.6E-05	2.5E-03	2.53E-03	100	<0.01%
	Eastern Whip-poor-will	7.6E-05	2.5E-03	2.58E-03	100	<0.01%
	Purple Finch	4.8E-05	1.9E-03	1.95E-03	101	<0.01%
	Ruffed Grouse	4.0E-04	5.0E-04	8.95E-04	100	<0.01%
	Belted	5.3E+00	2.8E-06	5.27E+00	100	5.27%

Taxa	Indicator	Dose due to waterborne emission (µGy/h)	Dose due to airborne emission (µGy/h)	Total dose (µGy/h)	Benchmark (µGy/h)	% of Benchmark
	Kingfisher					
	Bald Eagle	5.2E+00	8.9E-05	5.21E+00	100	5.21%
	Mallard	5.0E+00	2.8E-06	4.97E+00	100	4.97%
	Great Blue Heron	5.3E+00	2.8E-06	5.27E+00	100	5.27%
Invertebrate	Earthworm	0.0E+00	7.5E-04	7.50E-04	100	<0.01%
	Crayfish	8.1E+00	0.0E+00	8.11E+00	400	2.03%

The predicted doses to all indicator species of concern are below dose benchmark values specified in CSA [8-10]. Doses to Belted Kingfisher and Great Blue Heron, the most exposed indicator, are estimated to be 5.3 µGy/h, representing 5.3% of the benchmark value for terrestrial species.

8.5.2.2 Bathtub Effect Overflow Scenario

Although unlikely, due to the presence of multiple engineered barriers in the cover, it is assumed that the “Bathtub” scenario may occur following the closure of the NSDF, immediately after the end of Institutional Control. Under this scenario, rainwater is progressively penetrating through the eroded cover resulting in water ingress into the waste, a process similar to that described above. However, under the “Bathtub” scenario, the base liner system of the ECM is assumed to continue to perform as intended for a much longer period of time. If such a failure occurred, it would be possible for water entering the ECM to create a “Bathtub” effect, with the waste becoming fully hydrated and contaminated water eventually overtopping the ECM’s containment and leaching into the ground or surface water system outside of the ECM (see Figure 8-6).

Furthermore, it was conservatively assumed that the contaminated water flowing out of the ECM due to the “Bathtub” effect, will discharge directly into Perch Creek without any reduction in concentrations due to decay or dispersion in the groundwater.

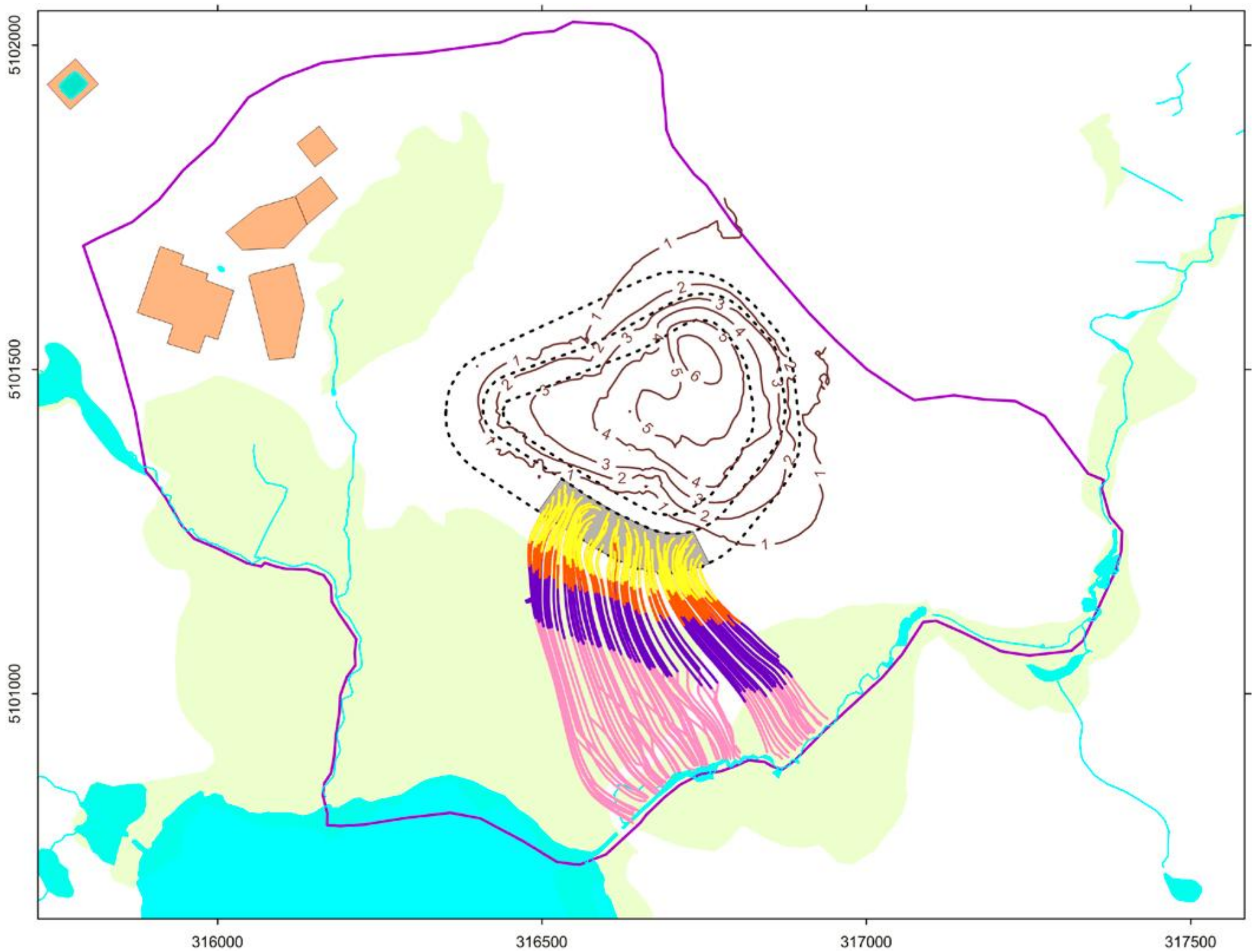

Figure 8-6 Conceptual Representation of the "Bathtub" Scenario [8-3]

The flux of radionuclides leaving the ECM in the overflow water, F (Bq/y), can be estimated as follows [8-3]:

$$F = \frac{Q}{L \times W \times T \times \theta \times Rd} \times q(L \times W) = \frac{Q\,q}{T\theta\,Rd}$$

Where

Q = inventory in the ECM (Bq, see Table 8-2)

L, W, T = the length, width and thickness of the ECM respectively (350 m, 285 m, 13.83 m)

ϴ= the moisture content (0.266)

Rd = the retardation factor (see below)

q = Infiltration rate (0.3m/y)

The retardation factor can be calculated using the following equation:

$$R_d = 1 + K_{da}\frac{\rho_a}{\eta}$$

Where:

η= the effective porosity of the contaminated zone (0.266)

K_{da} = the distribution coefficient in the contaminated zone (radionuclide specific [8-7])

ρ = the bulk density of the contaminated zone (1.5 g/cm^3)

The resulting radionuclide flux in the overtopping leachate is presented in Table 8-6.

Table 8-6 Flux of Radionuclide flowing out of the ECM

Radionuclide	Flux out of contaminated zone (Bq/y)
Ac-227	1.31E+06
Ag-108m	3.07E+06
Am-241	9.50E+07
Am-243	6.39E+04
C-14	3.02E+10
Cl-36	4.51E+08
Co-60	1.41E-08
Cs-135	2.59E+05
Cs-137	3.20E+09
H-3	3.56E+06
I-129	1.18E+09
Mo-93	3.77E+03
Nb-93m	6.82E+07
Nb-94	1.69E+08
Ni-59	6.87E+06
Ni-63	1.68E+08
Np-237	4.80E+06
Pa-231	1.60E+04
Pb-210	7.21E+07
Po-210	7.10E+08
Pu-239	2.61E+07
Pu-240	3.95E+07
Pu-241	1.53E-02
Pu-242	1.23E+05
Ra-226	3.75E+06

Radionuclide	Flux out of contaminated zone (Bq/y)
Ra-228	1.65E+07
Se-79	1.41E+05
Sn-126	1.01E+05
Sr-90	4.09E+07
Tc-99	4.01E+11
Th-228	1.75E+06
Th-229	5.32E+02
Th-230	1.06E+04
Th-232	1.75E+06
U-233	8.75E+05
U-234	1.80E+08
U-235	1.16E+07
U-236	1.61E+03
U-238	5.78E+08
Zr-93	3.41E+07

Doses to members of PCGs, located downstream from the Perch Creek outfall, were estimated using IMPACT 5.5.1 code, using the compartmental model described in Section 1.9.2 and using waterborne emission rates provided in Table 8-6. The results are summarized in Table 8-7.

Table 8-7 Doses to PCGs due to Exposure to Waterborne Emission for "Bathtub" Scenario (Event at year 2400)

Receptors	Dose to adult (mSv/y)	Dose to 10 year old Child (mSv/y)	Dose to one year old infant (mSv/y)
Cottager	3.2E-06	3.1E-06	2.2E-06
Pembroke	1.1E-04	1.6E-04	2.6E-04
Petawawa	1.1E-04	1.6E-04	2.5E-04
Laurentian Valley	8.6E-05	1.4E-04	2.4E-04

The maximum estimated dose to members of PCGs is 2.6E-04 mSv/y and the critical group is represented by one year old infants in Pembroke. This is 0.03% of the regulatory dose limit of 1 mSv/y and 0.09% of the dose constraint of 0.3 mSv/y and more than half of the estimated dose is from C-14, as shown in Figure 8-7.

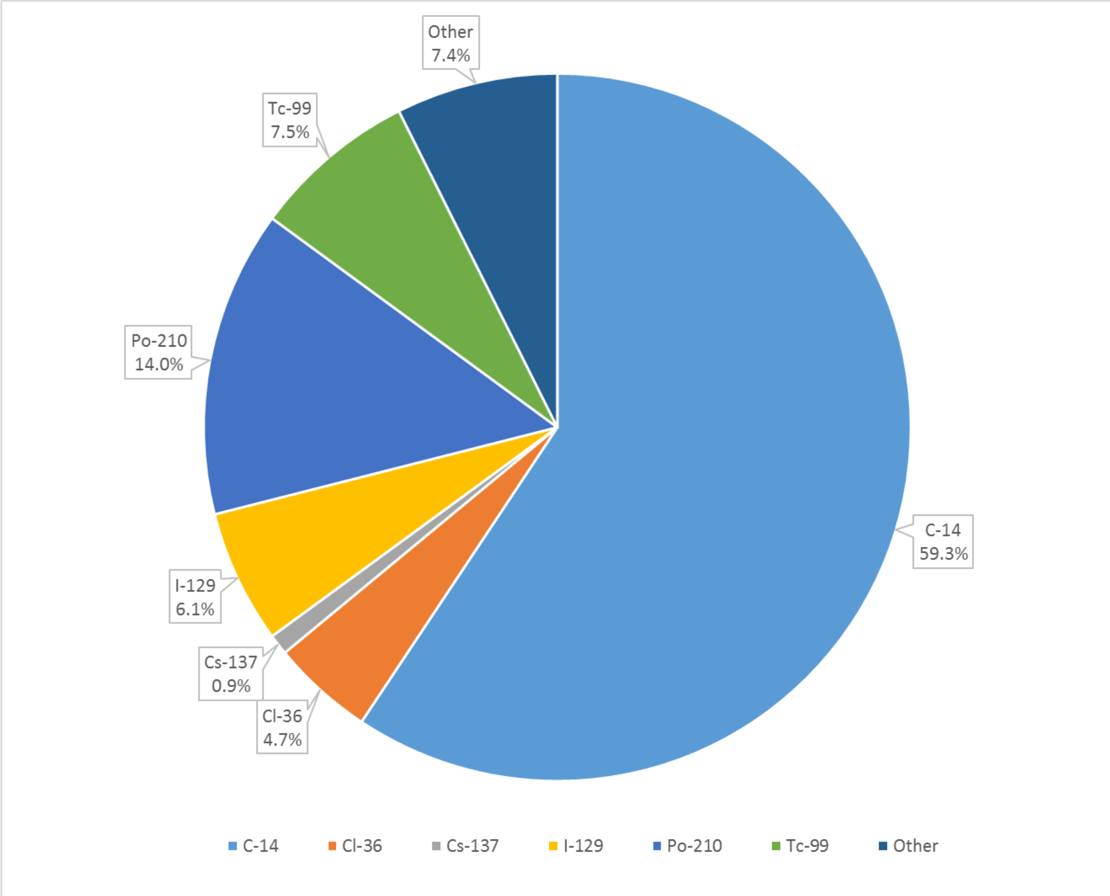

Figure 8-7 Percent Contribution by Radionuclide for Predicted Dose to an Infant in Pembroke (Bathtub Scenario)

Doses to indicator species were estimated using the method specified in CSA N288.6-12 [8-10] using the same approach as for the Operational Period (see Section 7.3). The estimated doses to non-human biota are shown in Table 8-8.

Table 8-8 Doses to Indicator Species due to Exposure to Waterborne Emission for “Bathtub” Scenario

Category	Indicator	Dose due to waterborne emission (µGy/h)	Dose due to airborne emission (µGy/h)	Total dose (µGy/h)	Benchmark (µGy/h)	% of Benchmark
Aquatic Plant	Reed	3.5E+01	0.00E+00	3.5E+01	400	8.6%
Fish	Bluntnose minnow	3.0E+01	0.00E+00	3.0E+01	400	7.5%
	Black	3.0E+01	0.00E+00	3.0E+01	400	7.5%

Category	Indicator	Dose due to waterborne emission (µGy/h)	Dose due to airborne emission (µGy/h)	Total dose (µGy/h)	Benchmark (µGy/h)	% of Benchmark
	Bullhead					
	Pike	3.0E+01	0.00E+00	3.0E+01	400	7.5%
Terrestrial Plant	Red Maple	0.0E+00	1.80E-03	1.8E-03	100	<0.01%
Insect	Monarch Butterfly	0.0E+00	1.70E-03	1.7E-03	100	<0.01%
Mammal	Little brown Myotis	7.7E-05	2.40E-03	2.5E-03	100	<0.01%
	Meadow Vole	2.3E-04	4.70E-04	7.0E-04	100	<0.01%
	White-tailed deer	6.5E-02	2.00E-03	6.7E-02	100	0.07%
	Short-tailed Shrew	1.5E-04	9.10E-04	1.1E-03	100	<0.01%
	Eastern Wolf	1.7E-01	4.00E-03	1.8E-01	100	0.18%
Reptile	Snapping Turtle	1.3E+01	0.00E+00	1.3E+01	100	13.4%
	Common Watersnake	1.3E+01	0.00E+00	1.3E+01	100	13.3%
	Eastern Milksnake	0.0E+00	7.50E-04	7.5E-04	100	<0.01%
Amphibian	Green Frog	1.3E+01	0.00E+00	1.3E+01	100	13.4%
Bird	Canada Warbler	5.4E-05	2.50E-03	2.6E-03	100	<0.01%
	Eastern Whip-poor-will	1.6E-04	2.50E-03	2.7E-03	100	<0.01%
	Purple Finch	1.0E-04	1.90E-03	2.0E-03	100	<0.01%
	Ruffed Grouse	8.3E-04	5.00E-04	1.3E-03	100	<0.01%
	Belted Kingfisher	5.9E+00	2.80E-06	5.9E+00	100	5.9%
	Bald Eagle	1.1E+01	8.90E-05	1.1E+01	100	11.4%
	Mallard	9.0E+00	2.80E-06	9.0E+00	100	9.0%
	Great Blue Heron	7.5E+00	2.80E-06	7.5E+00	100	7.5%
Invertebrate	Earthworm	0.0E+00	7.50E-04	7.5E-04	100	<0.01%
	Crayfish	5.9E+01	0.00E+00	5.9E+01	400	14.7%

Predicted doses to all indicator species of concern are below the dose benchmark values specified in CSA [8-10]. The most exposed species is Crayfish and dose to this indicator species is estimated to be 59 µGy/h, representing 14.7% of the benchmark value for aquatic species.

8.6 Disruptive Scenarios

This section summarizes the evaluation of postulated disruptive events which might occur after the closure of the NSDF. These events were identified as a result of the review of FEPs that may occur over very long periods of time, after the end of Institutional Control (see Section 8.3 and reference [8-1]). As for the Normal Evolution, it is assumed that Institutional Control will remain in place for 300 years after the end of decommissioning and final closure of the NSDF, which is projected to be completed in year 2100. As such, the post-institutional period will start in year 2400.

The disruptive event scenarios considered in this section are:

- Inadvertent human intrusion, "Acute" exposure scenario, involving drilling a borehole into the waste.
- Inadvertent human intrusion, "Chronic" exposure scenario, involving an intruder taking up residence on top of the ECM, consuming produce grown in contaminated soil and ingesting contaminated water.
- Glaciation scenario, which involves accelerated erosion of the cover and ultimate exposure of the waste following melting of the glacier.
- Failure of the ECM due to a beyond design seismic event, resulting in failure of engineered berms and cover.

Other disruptive scenarios are included as sensitivity cases (see Section 8.8.2)

8.6.1 Human Intrusion

IAEA [8-11] defines "Human Intrusion" as:

> *Human actions that affect the integrity of a disposal facility and which could potentially give rise to radiological consequences. Only those human actions that result in direct disturbance of the disposal facility (i.e. the waste itself, the contaminated near field or the engineered barrier materials) are considered.*

The CNSC postulates that Human Intrusion involving direct disturbance of disposed wastes needs to be considered, but only for inadvertent intrusion scenarios [8-2]. It is further stated that, probability and consequences of inadvertent intrusion are to be considered, and that the near-surface disposal is more likely to result in intrusion rather than geological disposal.

International organizations, such as IAEA, ICRP and OECD, provide the overall framework for defining Human Intrusion scenarios. In particular, International guidance [8-12], [8-13] and [8-14] states that:

- Some form of inadvertent Human Intrusion has to be considered in the context of disposal facilities after the end of the Institutional Control period. Intrusion should be assumed to occur at some time following the loss of knowledge about the site and its hazardous contents.

- Legal dose limit to individual members of the public does not apply to these scenarios and some form of optimization has to be applied.
- Analysis should include stylized intrusion scenarios reflecting site-specific conditions, inventory and design. It is not required to try and predict actual human behaviour during the post-Institutional Control period.

The active period of the NSDF construction and operation will involve a range of activities, such as placement of wastes within the ECM, monitoring and the installation of an engineered cover. During this period, there is human action at the facility, operational activities will be undertaken in compliance with regulatory and site requirements. By definition, inadvertent human intrusion is excluded from this phase of the NSDF lifecycle. The active Institutional Control period begins with the installation of the engineered cover and continues until Institutional Control of the facility and site is relinquished. During this phase, it is anticipated that the facility will be monitored and that there will be security in place at the site, preventing any unauthorised access. Therefore, it is assumed that there is no possibility for any inadvertent human actions that could damage the safety functions of the facility.

At the end of active Institutional Controls, there can be a period of passive controls that persists for as long as there is public knowledge of the site and the hazard it presents. Within the passive Institutional Control period it is anticipated that, records will be maintained for any radioactive waste disposal facility at the local, national and International levels for many centuries. While it may be possible that there could be minor, unauthorised inadvertent intrusion, there will be no major construction or excavation activity that would require any form of planning, consent or authorisation. The 100% design includes provisions of fencing and intrusion barriers.

The period of active and passive Institutional Control is assumed to end in the year 2400, i.e. 300 years from closure (in year 2100), which is consistent with International and Canadian practice for disposal facilities (e.g. [8-14]). Beyond this period, there are no expectations in this PA with respect to any ongoing societal control, monitoring or memory of the site.

An ongoing IAEA project entitled “Human Intrusion in the context of Disposal of Radioactive Waste” (HIDRA) developed a framework for selection of human intrusion scenarios (Figure 8-8).

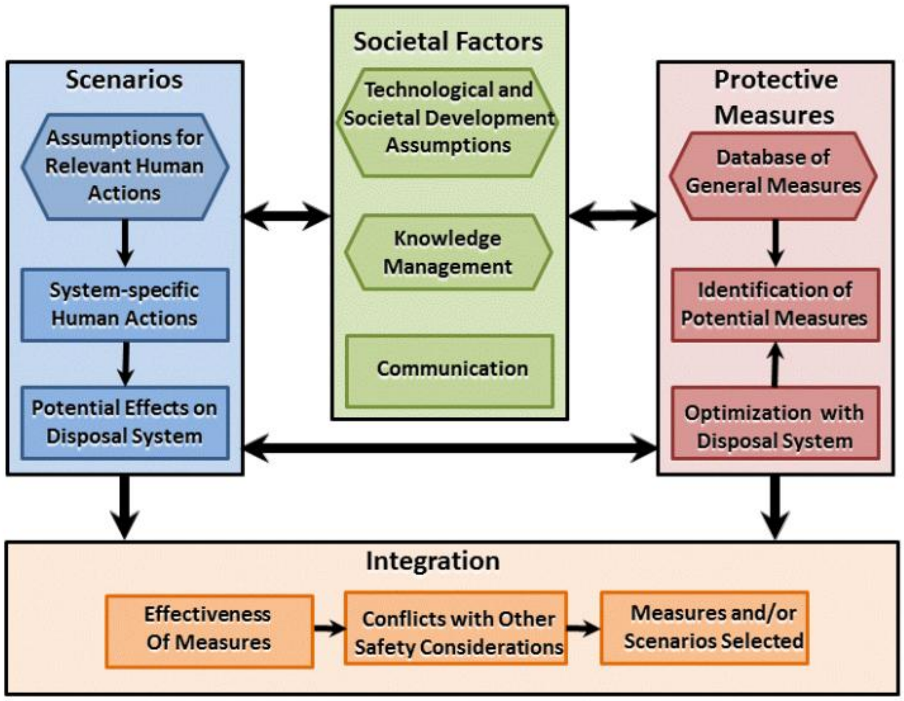

Figure 8-8 Framework for Selection of Human Intrusion Scenarios [8-15]

There are a number of possible human intrusion scenarios that could occur, including: geotechnical excavation, foundations for buildings, archaeological excavation, scavenging, and water abstraction wells. Given the lack of geological or archeological assets at the site, the chances of a human intrusion from this is low. As such, scenarios based around people living above the waste, and drilling water abstraction well have been considered (with the depth of the basement being considered as a sensitivity case).

8.6.1.1 Key Assessment Assumptions

The following assumptions have been made in developing Human Intrusion scenarios for the NSDF, in accordance with recommendations made by the HIDRA project (based on international best practices):

- Loss of knowledge of the repository.
- Intrusion occurs (even taking into account that the NSDF is located in a remote site with low human activities).
- Intrusion may occur immediately following the end of active control period (to minimise the effect of radioactive decay).
- Intrusion occurs within the ECM footprint.
- No loss of inventory due to leaching prior to intrusion. This is a conservative assumption, which maximizes the available inventory.

- Placement of a house on the top of the radioactive waste mound.
- Drilling of a water well. Drilling may disturb an area where a particular waste stream is disposed. Therefore, a higher-concentration inventory is considered as defined in Table 8-3.
  - It should be noted that drilling through the full depth of the waste (13.83 m) and hitting only the limiting packages is not probable. The bunker inventory used in this assessment (Table 8-3) represents ~98th percentile in terms of activity of key radionuclides in the context of intrusion. The likelihood of not just intruding, but also hitting *the* worst case package is low. Furthermore, high activity waste will be placed at the bottom of the ECM, with "select waste" and other lower activity categories at higher elevations. This means that in the retrieval of a full column of waste (>13m); it is not possible for the retrieved waste to include average concentration at limiting activity levels.
- The drill will not deflect around barriers, containers or waste forms.
- The driller/construction worker will not recognise that something is wrong and stop.
- Use of a well for water without considering water quality.
- Residents establishing home/farm specifically on the excavated material.
- Some of the cuttings are respirable.
- Cuttings will behave like soil with respect to uptake in plants.
- Conservative bias for exposure assumptions for occupancy and local food production and consumption, rather than those relevant to typical situations. More specifically, residents are assumed to have a 100% local food fraction. Additionally, occupancy on the primary contamination area is assumed to be 50% indoor and 50% outdoor.

A combination of International and Canadian framework for the assessment of Human Intrusion with site-specific conditions resulted in the formulation of two intrusion scenarios: Acute Exposure from Human Intrusion and Chronic Exposure from Human Intrusion.

The following assumptions were made for both acute and chronic exposure scenarios:

- Human intrusion can take place at any time after the end of Institutional Control (year 2400). No credit is taken for low probability of such an event or remoteness of location.
  - Additionally, as discussed at the start of Section 8, additional intrusion times are considered to assess the sensitivity of these cases to time of intrusion. These additional intrusion times are year 2200 and year 2300.
- Drilling may disturb an area where a particular waste stream is disposed (Bunker waste). Therefore, a higher-concentration inventory is considered as defined in Table 8-3.
- Inhalation rate, transfer factors, consumption rates, and other exposure parameters are consistent with CSA N288.1-14 [8-7] if applicable. Otherwise, RESRAD default values are used.

1. H.I. Main – Acute Exposure from Well Drilling

The acute scenario (Figure 8-9), is intrusion into waste when drilling a well. This scenario includes exposure to contaminated excavated material assumed to occur through inhalation, external exposure and soil ingestion.

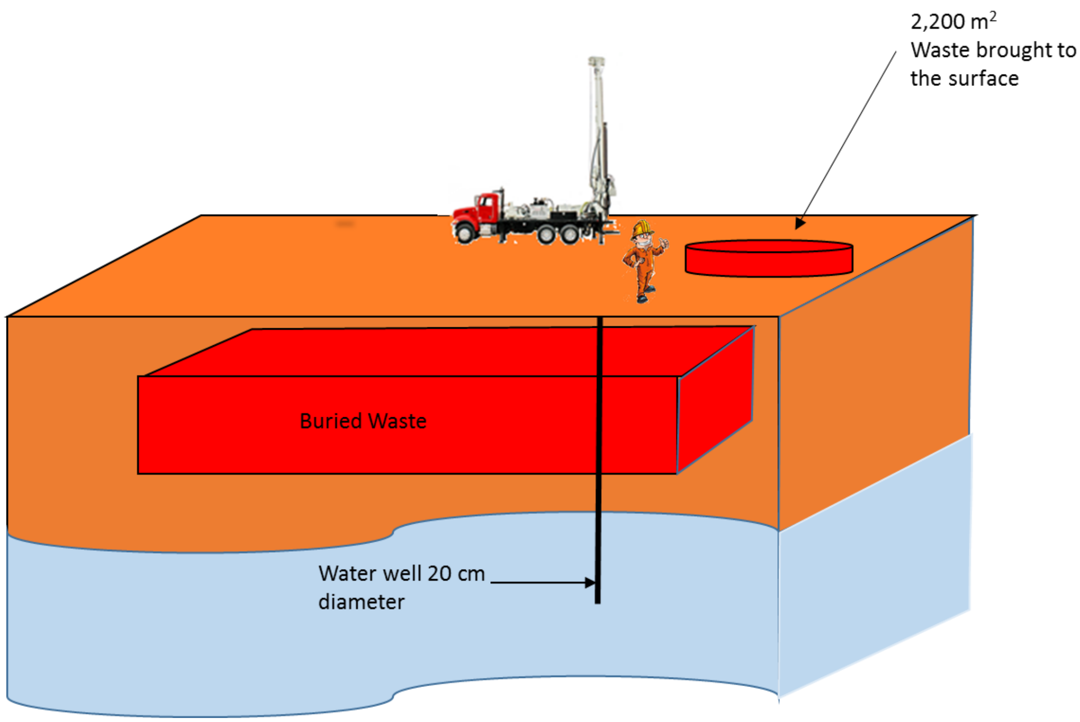

Figure 8-9 Intrusion - Acute Exposure Scenario

The following assumptions were made for the acute intrusion scenario:

- A 20 cm diameter well is drilled into the ECM. This diameter is consistent with large industrial water intake wells that are used in the region.
- The well is drilled through the full depth of the waste and through the 10 m of overburden to a combined depth of 30 m. This is consistent with local hydrogeological conditions and waterbearing capacities of the upper and baserock aquifers in the ECM location.
- A total of 0.53 m^3 of contaminated waste (conservatively represented as bunker waste, as discussed above and shown in Table 8-3) is being brought to the surface during drilling, which is mixed with 0.41 m^3 of clean material extracted during drilling from above and below waste.
- The exposure takes place over a period of three eight-hour days, which, again, is a typical duration for drilling a well of given dimensions.
- The receptor is treated as a member of the public who is drilling the well
- The intruder stays next to the drilling equipment on the surface of the ECM.

- Exposure pathways that are conservatively considered are inhalation of drilling dust, ingestion of contaminated soil, and, external gamma radiation from the extracted material.

2. H.I. Main – Chronic Exposure from Living on ECM

The chronic scenario (Figure 8-10) involves intrusion into the waste while inhabiting a dwelling on top of the ECM, using a residential well drilled into the ECM and mixing of exhumed waste with garden soil. Exposure pathways include inhalation, external exposure, soil ingestion, and ingestion of contaminated food (i.e. beef, milk, and plants).

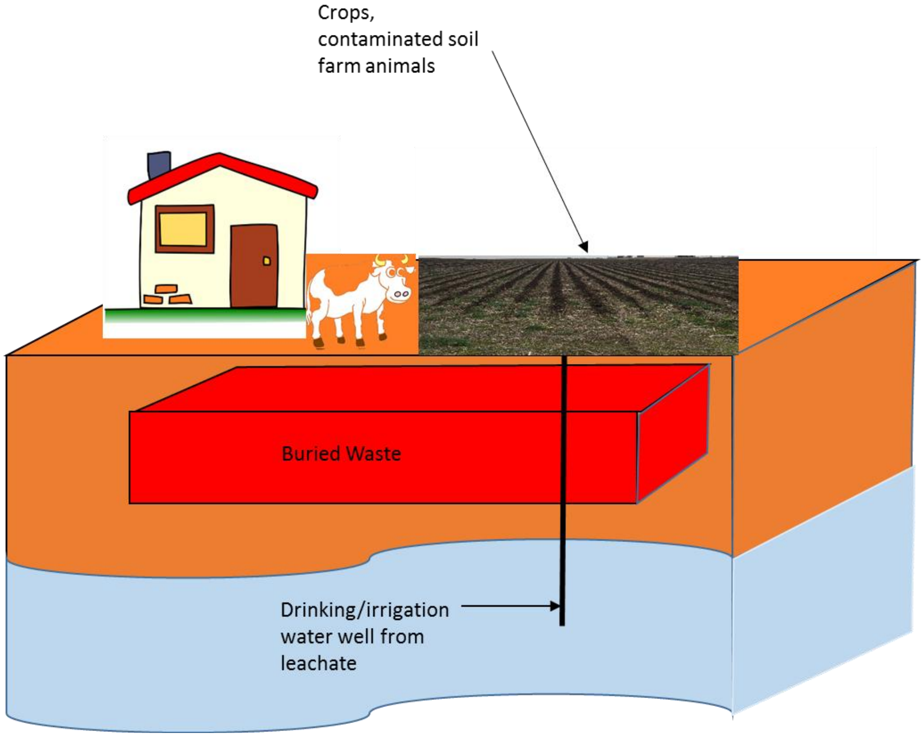

Figure 8-10 Intrusion - Chronic Exposure Scenario

The following assumptions were made for the chronic intrusion scenario:

- The receptor is a farmer living and farming on top of the ECM
- Exposure pathways considered include inhalation, external exposure, soil ingestion, ingestion of contaminated food (i.e. beef, milk, plants, and aquatic foods), ingestion of contaminated water, and exposure to radon.
- For the purposes of water use, a well is assumed to be located immediately downstream (groundwater) from the ECM and abstracts undiluted leachate, which is derived from the total inventory stored within the ECM (Table 8-2).
- For the purposes of estimating the waste brought to the surface, a 20-cm diameter well is assumed to be drilled through the waste.

- Contaminated drill cuttings (0.53 m^3) are spread across the field and mixed in with the soil from which vegetable crops are gown.
- The cuttings are spread across a vegetable patch with an area of 2 200 m^2 or approximately half an acre of the land surface to a depth of 61 cm, giving a total volume of the soil of 1 342 m^3.
- The dwelling site has a 1 m foundation (used for the purposes of radon ingress).
- It is assumed that the resident eats local aquatic food (from perch creek)
  - Fish at a rate of 5.4 kg/y – 0.5 local fraction
  - Crustacea and molluscs at a rate of 0.9 kg/y – 0.5 local fraction

8.6.1.2 Input Parameters

The resulting doses were evaluated using RESRAD-OFFSITE (see Section 1.9.3).

The key modelling parameters related to the intrusion scenarios described previously are summarized in Table 8-9.

Table 8-9 Key Modelling Parameters Related to the Intrusion Scenarios

Modeling parameters	Unit	Acute exposure (well drilling)	Chronic exposure (farming resident)
Volume of waste brought to surface	m^3	0.53	0.53
Area of contaminated area	m^2	2200	2200
Thickness of contaminated area	m	0.0005	0.61
Thickness of clean cover	m	0	0
Occupation factor (indoors)	unitless	0.00	0.50
Occupation factor (outdoors)	unitless	0.0028[1]	0.40
Exposure time	y	1	1
Inhalation rate	m^3/y	10400	10400

Note:
* Where RESRAD-offsite default values are used, they are not listed in this table.
[1] 0.0028 occupation factor corresponds to spending 24 h (3 x 8h days) at the site in a given year

The NSDF location and its surroundings are comprised of hilly terrain, with many marshes and rocks, and otherwise poor soil quality for growing crops. The amount of space that would be usable for growing produce in minimal. From this, post-closure calculations assume that all vegetables and grazing vegetation is grown within the 2,200 m^3 contaminated area. This is conservative because if vegetables or grazing vegetation were to be grown outside of this area, then the concentrations of contaminants in the soil - and therefore in the vegetation - would be lower, and lead to a lower total dose.

8.6.1.3 Results

Doses to drilling workers and farm resident were calculated using RESRAD 3.1. The results are presented in Table 8-10 and Table 8-11.

1. H.I. Main – Acute Exposure from Well Drilling

Table 8-10 Dose to Drilling Workers

Time after the end of Institutional Control (years)	Total dose (mSv)
0 (at year 2400)	6.4E-03
100 (at year 2500)	5.7E-03
1000 (at year 3400)	3.6E-03

For the acute intrusion scenario, drilling workers are predicted to be exposed to the maximum dose if the work is carried out immediately after the end of Institutional Control. The estimated dose to drilling workers is 6.4E-3 mSv/y. This represents only 0.6% of the lower intrusion dose benchmark of 1 mSv/y. As shown in Figure 8-11 and Figure 8-12, the major dose contributors are Am-241 and Nb-94 and the key pathways are inhalation, external exposure to contaminated land, and incidental ingestion of contaminated soil.

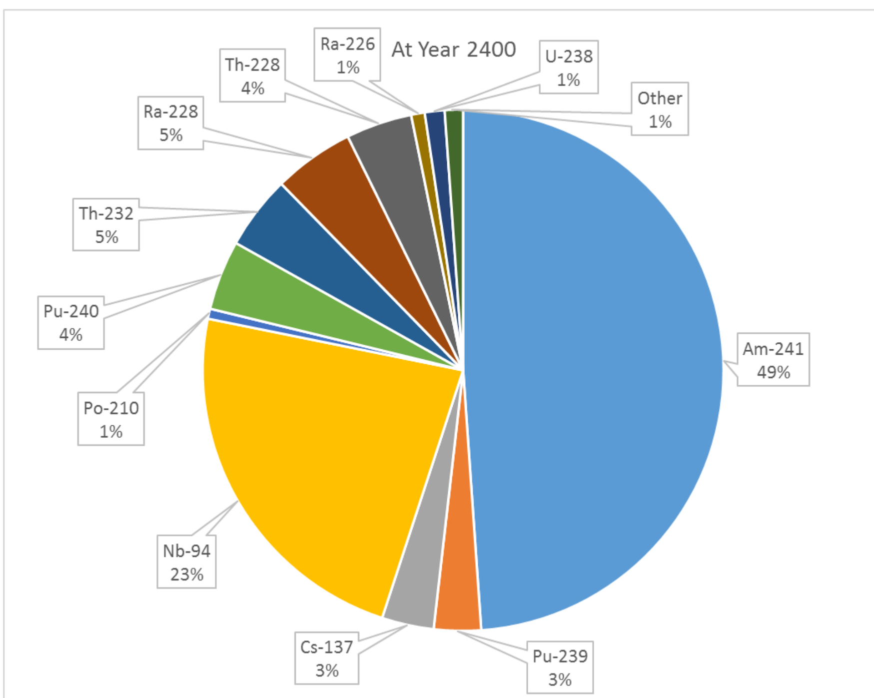

Figure 8-11 Percent Contribution by Radionuclide for Maximum Dose to Driller

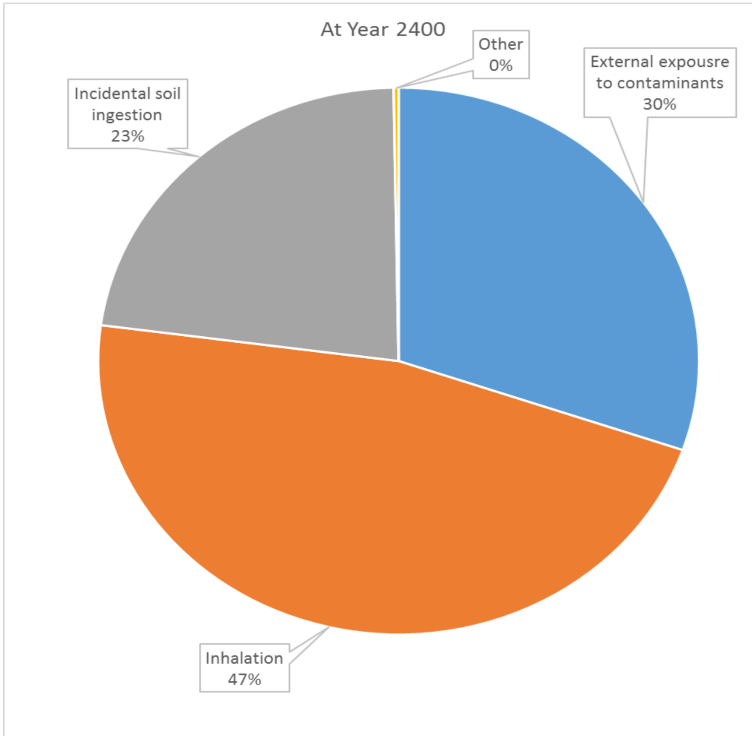

Figure 8-12 Percent Contribution by Pathway for Maximum Dose to Driller

2. H.I. Main – Chronic Exposure from Living on ECM

Table 8-11 Dose to Farm Resident

Time (years) after the end of Institutional Control	Dose due to exposure to surface contamination (mSv/y)	Dose due to waterborne emissions from the ECM (mSv/y)	Total dose (mSv/y)
0	1.1E-01	7.6E-01	8.7E-01
1	8.4E-02	8.2E-01	9.1E-01
10	8.0E-02	1.2E+00	1.2E+00
100	7.0E-02	1.1E+00	1.2E+00
500	6.4E-02	1.5E+00	1.5E+00
1,000	5.9E-02	2.0E+00	2.1E+00
5,000	3.5E-02	1.4E+00	1.4E+00
10,000	2.0E-02	2.2E+00	2.2E+00
54,218	4.0E-04	5.4E+00	5.4E+00
100,000	3.0E-05	4.9E+00	4.9E+00

For farming residents, the waste brought to surface as a result of well drilling is the primary source of contamination if intrusion were to occur soon after the end of Institutional Control.

For farming residents, the total dose was estimated to be 0.87 mSv/y if they live on top of the ECM immediately at the end of Institutional Control. The waste brought to surface as a result of well drilling, contributes only about 13% of dose to the residents and the dose due to the waste in the ECM account for 87% of the total dose.

Gradually, emissions from the waste become even more dominant contributors to the exposure of farming residents. The peak is reached approximately 54200 years after the end of Institutional Control with the farming resident receiving the maximum dose of 5.4 mSv/y. As shown in Figure 8-13 and Figure 8-14, the main dose contributor is Po-210, which is a daughter product from the Ra-226 decay chain, and the key pathways are ingestion of food and water. The predicted exposure levels exceed the lower benchmark of 1 mSv/y but are still below the upper dose benchmark of 20 mSv/y for human intrusion (see Section 2.4). This estimate is likely to substantially overestimate potential exposure to an intruder because it results from a very conservative assumption that no loss of inventory occurs in the period from placement of waste into the ECM and until intrusion occurs some tens of thousands of years later.

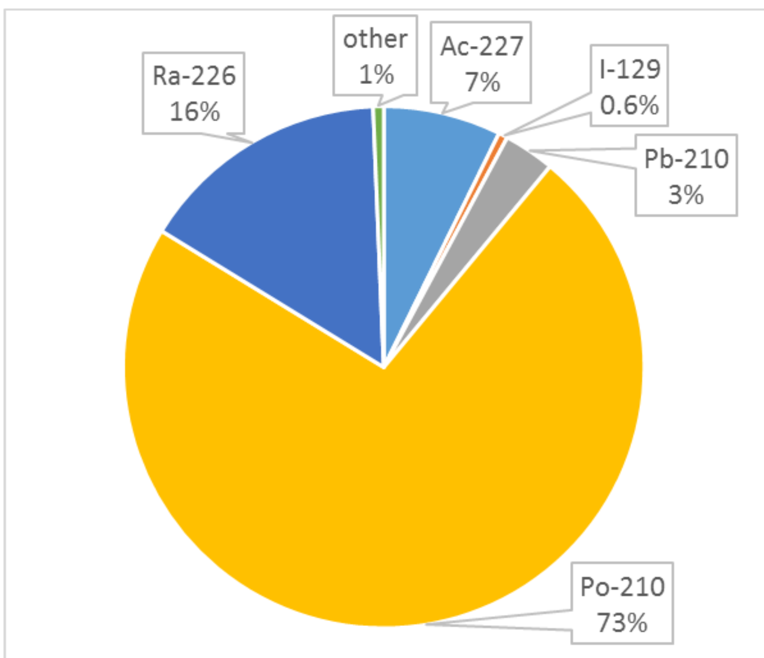

Figure 8-13 Percent Contribution by Radionuclide for Maximum Dose to Farming Resident

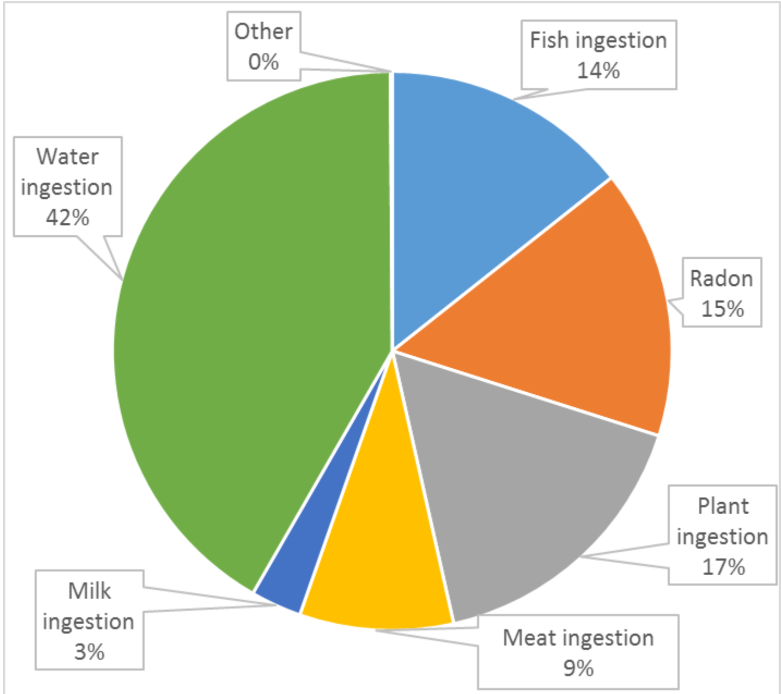

Figure 8-14 Percent Contribution by Pathway for Maximum Dose to Farming Resident

3. Summary

In summary, land use control measures will ensure that no inadvertent human intrusion can occur for at least 300 years after site closure. Following that, if Institutional Control were to be lost due to societal or political upheaval, a number of measures will be implemented through design to decrease the chance that the inadvertent human intruder will drill a water well into the waste. For example, the NSDF will be designed to provide a range of protective measures, including:

- Site Recognition.
- Waste Recognition.
- Markers and Placards.
- Passive Barriers.

8.6.2 Glaciation Event

The climate of the Earth has changed throughout history, from glacial periods where ice covered significant portions of the planet to interglacial periods such as today, when glacier retreated to the poles. Ontario could be subjected to a glaciation event, similar to those that have occurred in the past. It is likely that the next glaciation cycle has been delayed by some tens of thousands of years due to global warming (see Section 3.6.2); however, the possibility should be considered over very long timescales.

An illustrative glacial cycle for the Canadian shield was described by NWMO [8-16] based on several plausible histories as developed by Peltier [8-17]. Based on this historical analysis, the NWMO assumed that the next glaciation will not occur in less than 60,00 years. This assumption was conservative and appropriate for the requirements of NWMO.

However, for evaluating the potential impacts on NSDF, we need to estimate a future glaciation scenario from the most current understanding of this scenario. Based on cumulative carbon emissions (1,000 to 1,500 gigatonnes of carbon), it is currently projected that the next glaciation event will not occur for at least 100,000 years [8-4] and that the ice sheet may retreat after some 40000 years from the start of glaciation.

Glaciation can impact the NSDF performance by limiting infiltration of water into the facility and via permafrost arresting groundwater movement in the impacted strata. At the same time the environment will not be able to sustain human populations, resulting in the absence of potential receptors for radiological exposure. However, a heavy sheet of ice may impact the stability of the ECM. The glacier may also lead to deep erosion of the mound, resulting in dispersion of subsurface material once the glacier retreats. It is at this point that potential exposure of returning humans may occur.

Given inherent uncertainty, any possible exposures taking place following glaciation, natural analogues have been used to evaluate potential impact on humans in 100000 years (see Section 8.7).

It is also worth noting that a glacier has the potential to move some waste as a single mass (i.e. a container of bunker waste). The transportation of such a single mass could result in different exposures when compared to a source distributed over a large area, as it would be much more concentrated. This case would be bounded by the human intrusion coring case, as it will also result in exposure to a single mass of contamination material. Furthermore, in the human intrusion case, the waste will not be decayed by tens of thousands of years, as it would with the glaciation event, and as such is bounding.

8.6.3 Seismic Event

The ECM is located on a slope. If an external loading due to an earthquake were to produce larger forces than the resisting forces due to the shear strength of soil, the rupture of soil material located beneath the mound would take place. This type of failure could lead to a failure of engineered berms and cover.

Seismic design of the ECM ensures that the facility can withstand a high intensity, low-probability seismic event occurring near the CRL site, in accordance with the findings of PSHA (see Section 3.3.3). Seismic stability evaluations have been conducted for the ECM and the design ensures that safety requirements have been met (this reflected in the SAR). This assures the berms and final cover design are stable under seismic loading conditions. Furthermore, throughout the period of Institutional Control, the consequences of any damage can be mitigated.

However, since the facility will be in the post-closure phase for a very long time, the probability of a beyond design seismic event is greater. If it were to occur after the end of Institutional Control, sections of the containment provided by the ECM could be damaged, including the damage that could be sustained by berms and multi-layered engineered cover.

A limiting assumption about possible water flow is that, following a beyond design earthquake, infiltrating precipitation is unimpeded by the multilayered cover across the whole surface of the ECM. This assumption is consistent with infiltration rates assumed for the Normal Evolution scenarios, considered in Section 8.4. Therefore, consequences that could result from leaching of exposed waste into the groundwater, are also bounded by consequences already evaluated based on the bounding assumptions used for the Normal Evolution scenarios.

Furthermore, the residential human intrusion scenario already considers consequences resulting from exposure to waste material resulting from damage to the integrity of the ECM (Section 8.6.1).

Given that consequences from the bounding scenarios do not exceed the Safety Criteria, it can be concluded that this conclusion is also applicable to scenarios resulting from the ECM damage due to a seismic event after the end of Institutional Control.

8.7 Natural Analogues

Many naturally occurring ore bodies contain elevated concentrations of radionuclides. The most significant of these are uranium ore bodies, rock phosphate ore and mineral sand deposits [8-18]. The existence of these ore bodies provides a point of comparison for analysing the health and environmental impact of near surface waste repositories, in terms of the risk of harm associated with the NSDF disposal site, relative to the risk of harm associated with the naturally occurring ore body.

Many of the naturally occurring radionuclides present in these ores have very long radioactive decay times. This means that once relatively short lived radionuclides have decayed, the long-term impact of the near surface disposal of radioactive waste will be similar to the impact of ore bodies that already exist in the natural environment. Experience has shown that a sound knowledge of the potential radiological impacts associated with the presence of these natural ore bodies usually results in no measurable impacts on human health. These naturally occurring ore bodies can therefore, be used as an analogue for qualitative estimation of the potential impacts of the near surface disposal of radioactive waste.

In Canada, while most Uranium ore deposits are located at significant depths underground, there is also a large number of near-surface deposits in British Columbia, Nova Scotia, Yukon, and New Brunswick [8-19]. Canadian surficial uranium deposits occur in such diverse regions as semi-arid, alpine and permafrost terrains. Deposits of this type are formed at or within a few metres of the surface, often in swamps and river valleys. Several of such surficial deposits of Uranium are present in the Okanagan Valley region, including Prairie Flats fluvial deposits, located within the Summerland town limits.

At least two glacial advances have been recorded for the Okanagan region [8-20], both covering the entire region with continental-type ice sheets. Glacial activity ceased about 10000 years ago. Annual precipitation rates in the region vary from 400 to 700 mm, which at the higher rates, is consistent with the NSDF conditions.

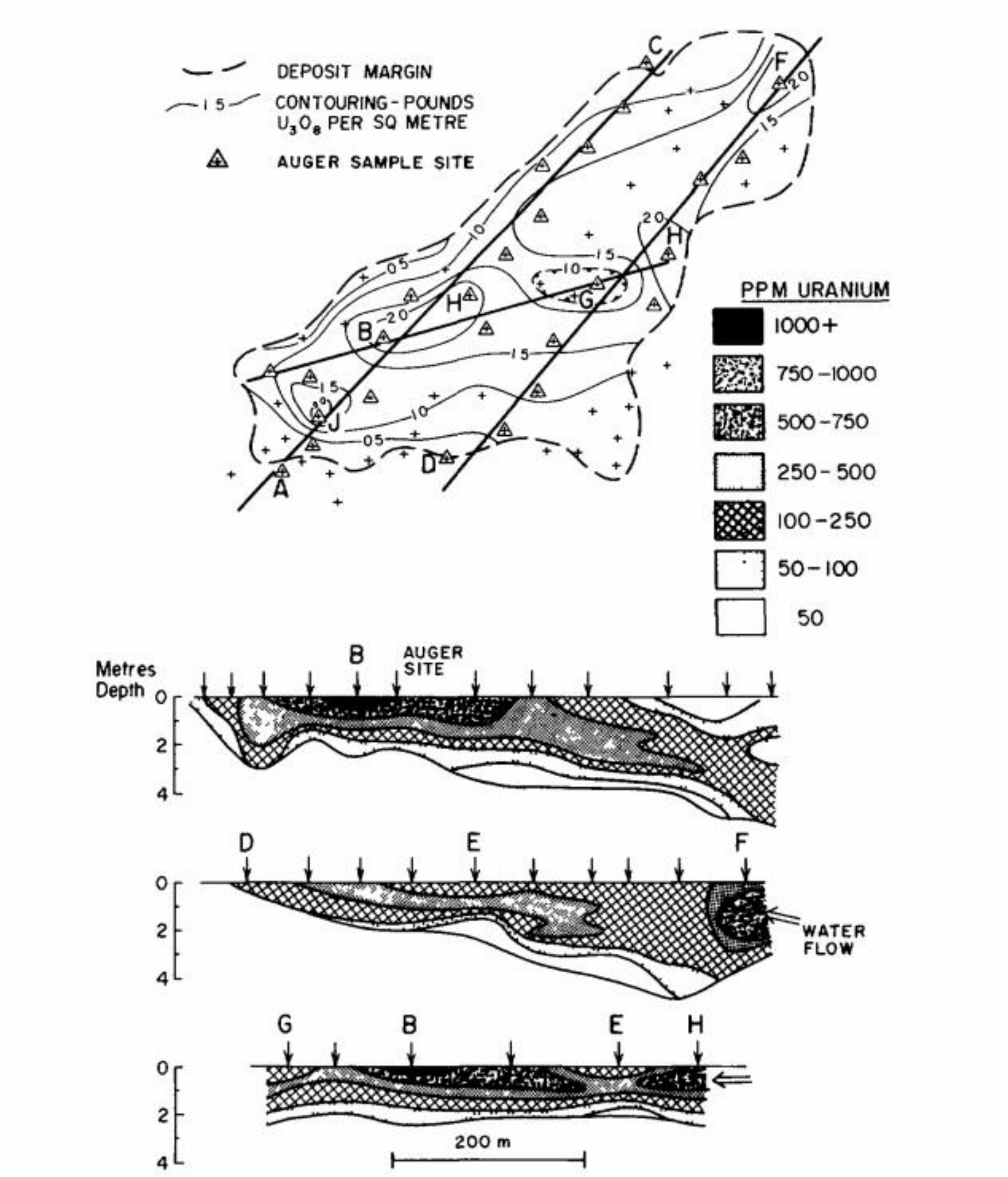

Figure 8-15 Distribution of Uranium in a Prairie Flats, Summerland Area [8-21]

Numerous valley-filled deposits in the Okanagan Valley region occur within swamps. A typical natural ore body will contain several million metric tonnes of ore, which is larger than the quantity of radioactive waste to be placed within the NSDF.

The Prairie Flats deposit near Summerland is a good example of surficial deposits of Uranium (see Figure 8-15). The greatest concentrations of Uranium, which locally exceed 1 000 ppm, occur in the surface layer. If we assume concentration of 572 ppm of U-238 (corresponding to the upper bound of concentrations found at Prairie Flats [8-22]), this corresponds to 0.572 g of U-238 per kg of soil, or an activity concentration of approximately 7 Bq/g. In a surficial Uranium deposit, U-238 is accompanied by other isotopes of Uranium and Thorium as well as their progeny, with U-234, Th-230 and Ra-226 trending towards equilibrium with U-238, depending on the age of the deposit. Assuming these three radionuclides are in equilibrium with U-238 and neglecting their progeny, it gives the total radionuclide concentration of 27 Bq/g. In practice, mobile progeny, including Ra-226 and its daughter radionuclide, leach out at very low concentrations over the centuries and do not accumulate within deposits. Similarly, the lower bound concentration of 3 ppm [8-22], results in a concentration of 0.1 Bq/g.

Unlike surficial Uranium deposits, the NSDF is designed to provide multiple barriers containing radioactive waste for many centuries. Long-term monitoring will be provided to detect any deficiencies in performance. Even allowing for the complete lapse of Institutional Control after year 2400, multiple barriers are likely to continue functioning and contain radioactive material. It is however feasible that the mound will undergo accelerated erosion leading to loss of containment at some point in the future when the region is subjected to the next glaciation cycle. It is predicted that the cycle will start more than 100,000 [8-4] years from now.

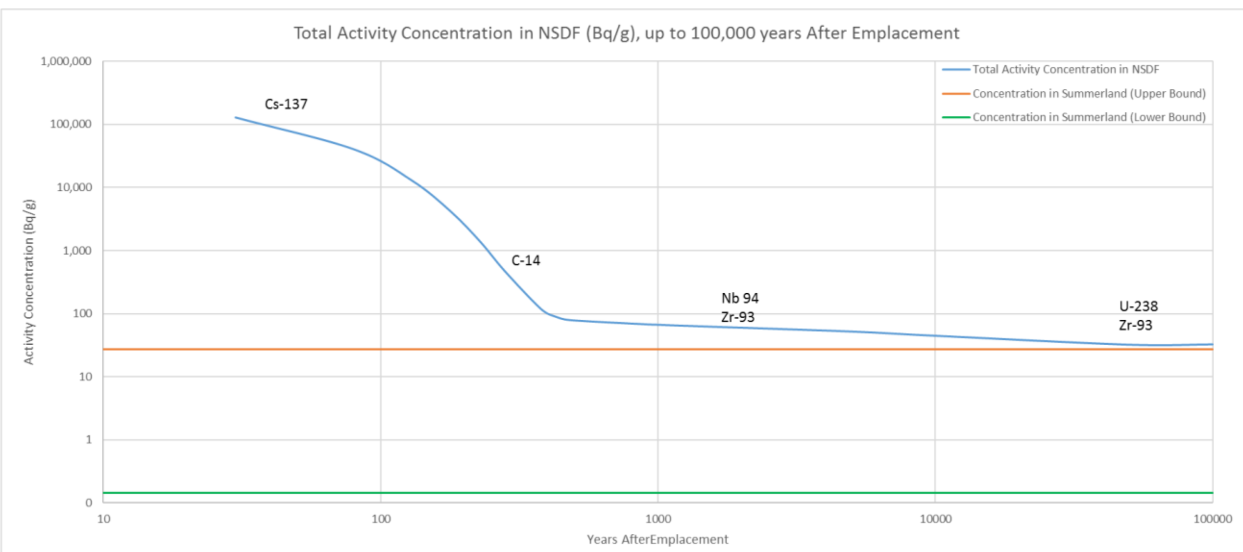

Figure 8-16 Concentration of Long-lived Radionuclides within the NSDF inventory vs Activity of Surficial Uranium Deposits Near the Town of Summerland, BC.

If this were to occur, the ECM would be eroded and containment would be lost. While Uranium and Thorium isotopes with high distribution coefficients may continue to be localized within the footprint and adjacent areas, mobile progeny would not accumulate over time, as in the case with natural analogues provided by surficial deposits. Figure 8-16 shows how the total activity varies over time and also shows the dominant radionuclide at various time periods. By the time the glacier retreats, radionuclide content will have decayed to the levels that are around what is typical for surficial uranium deposits in Canada. This includes the progeny of long-lived uranium and thorium isotopes, which will be at concentrations below natural analogues present in Canada. Radiological consequences to a hypothetical exposure group settling in the area after the retreat of the ice sheet will be bounded by the current levels of exposure to members of the public living in the vicinity of surficial Uranium deposits. In 2007, the Canadian Council of Ministers of the Environment reviewed environmental levels of radionuclides in soil, groundwater and vegetation in several locations containing Uranium deposits, including Summerland, and found that they meet Canadian Soil Quality Guidelines for Uranium and that "no adverse impacts are expected" [8-22].

8.8 Uncertainties in Post-Closure Analysis

Table 8-12 describes key uncertainties in assessing consequences from the Normal Evolution as well as alternative and disruptive scenarios, how conservatism in the analysis and assumptions addressed these uncertainties.

Table 8-12 Uncertainties in Post-Closure Assessment

Parameter	Assessment Scenario	Uncertainty	Conservatism and Assumptions
Inventory	All Scenarios	There is uncertainty with regards to the inventory of radionuclides that have been accumulated over the decades of operation of CRL site. It is not known what wastes may be generated by future operations at the CRL site and by external consigners of radioactive wastes which may be disposed at the NSDF.	• Both already accumulated wastes and those that will be generated in the future will have to meet the NSDF WAC as a control measure. • Estimates of the total ECM inventory were made conservatively, as described in Section 8.1. It is anticipated that the NRU reactor will be shut down in 2018 and isotope production has already ended. Higher activity waste streams will no longer be generated once operations cease. Decommissioning and Environmental Remediation waste streams are associated which much lower levels of radioactivity.
ECM Performance	All Scenarios	There is uncertainty with regards to when protective barriers may begin to fail due to erosion or other natural events.	• ECM includes multiple barriers in the cover and base liner, designed to isolate the waste even in the event if one or more of the barriers were to fail. This and other barrier systems support the defence in depth

Parameter	Assessment Scenario	Uncertainty	Conservatism and Assumptions
			approach. • The ECM can be maintained and monitored during the period of Institutional Control. Any issues identified during this period can be mitigated. • Two conservative scenarios involving major failures of the cover and base line were considered under the "Normal Evolution Scenario". It was assumed that the failures would occur immediately following the end of Institutional Control. • Predicted doses to the public are a small fraction of the regulatory limit and the dose constraint of 0.3 mSv/y.
Human habits	Normal Evolution	It is uncertain that future populations will maintain current habits, consumption rates, and that the location of population centers will not change.	• Normal Evolution scenario assumed that the current habits are maintained in the future, consistent with G-320. • To investigate sensitivity to changes in future human habits and location of potential exposure groups, several additional scenarios are considered in Section 8.8. Specifically, Case one: PCGs taking water from the Perch Creek outfall to the Ottawa River, assumes that the receptors take all water from the Perch Creek outfall, and that they eat 2 times more local food.
Conceptual model	Normal Evolution	This uncertainty is associated with the conceptual model for groundwater flow and potential future impacts on it resulting from the climate change.	• Current groundwater flow and contaminant transport in Perch Lake area are well understood thanks to the extensive period of characterization and monitoring in the Perch Lake Basin (see Sections 3.4 and 3.5). For further information please see [8-3] • Groundwater flow model was calibrated against the available data tests based on the existing plumes

Parameter	Assessment Scenario	Uncertainty	Conservatism and Assumptions
			emanating from WMA and LDA [8-3]. • For the "Bathtub" scenario, it was conservatively assumed that overtopping of contaminated leachate, results in an instantaneous discharge into Perch Creek. This provides a limiting assumption for any future changes that may occur.
Leaching and Transport parameters	Normal Evolution	Parameter uncertainty may lead to underestimation of doses to members of the public and non-human biota.	• The site characteristics are well understood, thanks to many decades of monitoring. In any case, conservative and bounding assumptions were used as described above. • Use of conservative values for sensitive parameters. A lower K_d for leaching from the ECM was considered in one of the sensitivity scenarios (see Section 8.8).
Exposure Duration and Pathways	Human Intrusion and other Disruptive Scenarios	Inherent uncertainty in the assumptions on human habits and the nature of intrusion scenarios, given the times scales involved.	• Case-specific scenarios were developed, taking into account parameters associated with typical current construction and residence in the region. • While there is a substantial degree of uncertainty associated with the analysis over such timescales, consideration of a range of scenarios that assume drilling into the waste, ingestion of contaminated foodstuffs and drinking from a well directly exposed to leachate, provides an envelope of conservative analysis and an indication of the level of risk. • There is an inherent uncertainty in disruptive scenarios. Even if it were to be assumed that there will be a complete loss of the legal system and knowledge of the facility, the NSDF will provide a range of human

Parameter	Assessment Scenario	Uncertainty	Conservatism and Assumptions
			intrusion barriers that would forewarn a potential intruder (see Section 6.2). • Sensitivity analysis considered consequences of drilling a substantially larger well than is typical in the region (see Section 8.8).
Impact of Environment on ECM	Disruptive Scenarios	Performance of the ECM barriers could be impeded by natural events, such as floods, weathering, animal borrowing, and fires destroying vegetative cover.	• Normal Evolution scenarios conservatively assumed failures of the cover and base liner immediately following the end of Institutional Control.
Modelling Tool uncertainty	All	Uncertainty associated with conceptual models built within RESRAD and IMPACT codes.	• Numerical uncertainty in the selected models has been evaluated through model verification. Model verification answers the question “Does the model accurately simulate the behaviour of the system?” Both RESRAD and IMPACT codes have undergone extensive verification for the pathways and exposure scenarios considered in the analysis (see Section 1.9).
Cumulative Effect	All	Uncertainty associated with the cumulative effect during post-closure, taking into account releases from WMAs and LDAs in the Perch Creek Basin.	• CNL is developing an appropriate environmental remediation concept for contaminated areas. The decision-making process is based on radiological impacts. It is expected that, if there is any potential to have significant cumulative effects, then contaminated land from WMAs and LDAs will be removed prior to the NSDF closure.

8.8.1 Sensitivity Analysis, Normal Evolution

8.8.1.1 Normal Sensitivity Case 1 – Drinking water from Perch Creek

The purpose of this sensitivity study is to investigate the maximum impact of waterborne emissions from the NSDF.

Under this scenario, a hypothetical group has been defined, that is living on the shores of the Ottawa River and is using the Perch Creek outfall to satisfy all water requirements, including drinking, bathing and irrigation. Dilution in the Ottawa River is not considered. The hypothetical group has also been assumed to consume locally produced food at twice the rates of the lifestyle survey results [8-9], including fish from the Ottawa River.

This scenario is summarized as follows:

- Based on:
    - Normal Evolution – Leaching Through the Liner
- Primary Difference:
    - All water is taken from the Perch creek outflow (where Perch Creek meets the Ottawa River
- Waste Considered:
    - Total Inventory (Table 8-2)
    - Located within the ECM
- Pathways Analysis:
    - Conducted using IMPACT
    - All pathways are considered
    - Fish ingestion is from the Ottawa River
- Event Time: Year 2400
- Peak Dose: 8 y after event (year 2408)

As shown in Table 8-13 peak doses to the hypothetical groups are in the range of 0.218 mSv/y to 0.322 mSv/y. This is less than the regulatory dose limit of 1 mSv/y, however, doses to one-year-old infant at Balmer Bay, Chalk River and Deep River (0.322 mSv/y, 0.316 mSv/y and 0.314 mSv/y respectively) marginally exceed the illustrative dose constraint of about 0.3 mSv/y. It should be noted that “about 0.3” mSv/y is an illustrative value provided by G-320. whereas the 1mSv/y is not exceeded. As shown in Figure 8-17 Tc-99 is the major contributor (>75% of total dose) to the peak dose estimated for the one-year-old infant at Balmer Bay which occurs 8 years after year 2400 for this sensitivity case.

As this result slightly exceeds the dose constraint of about 0.3mSv/yr, the PA recommends that one or more of the following measures be considered:

1. It is understood that the inventory activity concentrations used in this PA are very conservative. It is expected that a more realistic estimate of the Tc-99 inventory would result in a lower dose that would meet the dose constraint. Although this is simply a sensitivity analysis, such an estimate would strengthen the arguments for the robustness of the disposal concept.
2. The PA producing this result is conservative. Specifically, no credit is taken for waste stabilization and packaging in the RESRAD post closure calculations.

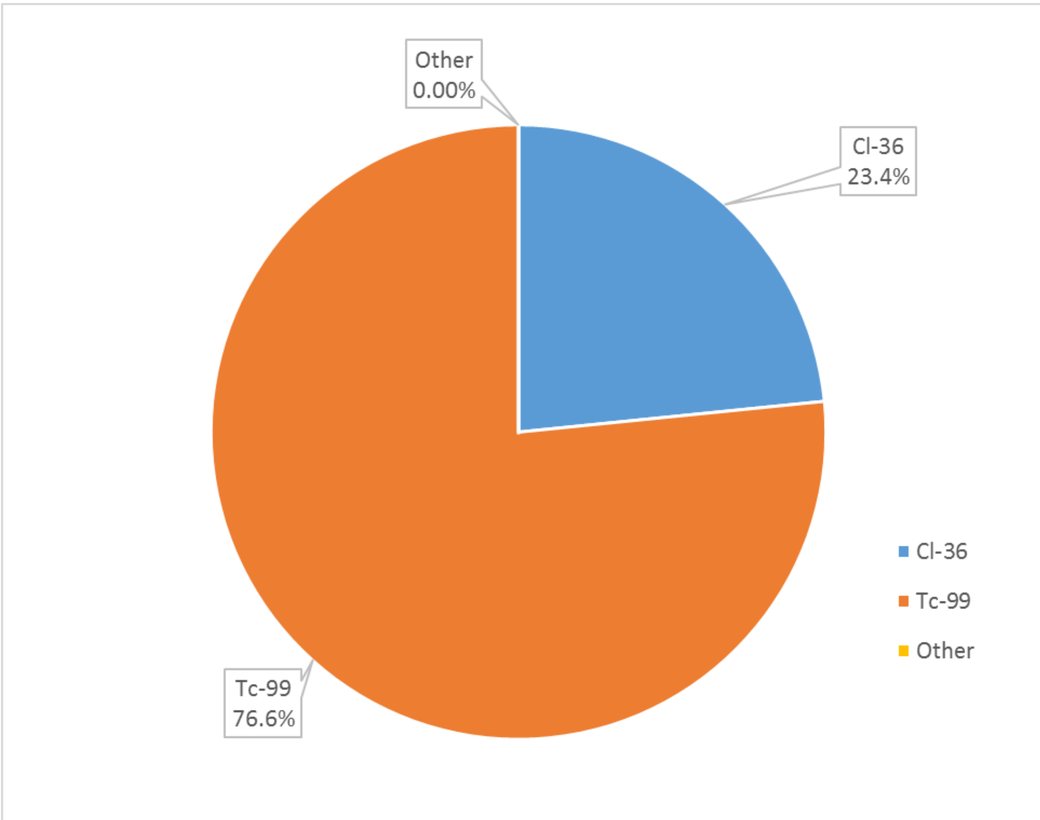

Figure 8-17 Percent Contribution by Radionuclide for Predicted Peak Dose to an Infant in Balmer Bay

Table 8-13 Peak Dose to Hypothetical Groups using Water from the Perch Creek Outfall for all their Needs

Location of PCGs	Adult			Ten year old children			One year old infant		
	Dose (mSv/y)	Ratio of criterion of 1mSv/y	Ratio of criterion of 0.3mSv/y	Dose (mSv/y)	Ratio of criterion of 1mSv/y	Ratio of criterion of 0.3mSv/y	Dose (mSv/y)	Ratio of criterion of 1mSv/y	Ratio of criterion of 0.3mSv/y
Balmer Bay	2.53E-01	0.25	0.84	2.84E-01	0.28	0.95	3.22E-01	0.32	**1.07**
Chalk River	2.50E-01	0.25	0.83	2.60E-01	0.26	0.87	3.16E-01	0.32	**1.05**
Deep River	2.40E-01	0.24	0.80	2.73E-01	0.27	0.91	3.14E-01	0.31	**1.05**
Mountain view	2.18E-01	0.22	0.73	2.46E-01	0.25	0.82	2.66E-01	0.27	0.89

Note: Ratios above 1 (i.e. dose exceeds criterion) are shown in **Bold** and shaded.

8.8.1.2 Normal Sensitivity Case 2 – Living Close to the NSDF

The purpose of this sensitivity study is to investigate the impact of **airborne emissions** from the NSDF as a result of erosion. Furthermore, it is conservatively assumed that the critical group is located closer than today's current receptor.

According to this scenario, the ECM's cover is damaged due to erosion and as a result, there will be airborne emissions from the ECM. The hypothetical group is assumed to live 500 m away from the NSDF site and consume locally produced food at twice the rates of the lifestyle survey results [8-9]. Note the impact of waterborne emissions which has been assessed before, is not considered for this scenario.

For modelling purposes, the airborne emission source is characterized as follows:

- The radionuclides are released at ground level.
- The emission rate was calculated using RESRAD OFFSITE 3.1

This scenario is summarized as follows:

- Based on:
  - Normal Evolution – Leaching Through the Liner
- Primary Difference:
  - Uses air releases only (not water)
  - Receptor is closer to NSDF site (500 m from the site)
- Waste Considered:
  - Total Inventory (Table 8-2)
  - Located within the ECM
- Pathways Analysis:
  - Conducted using IMPACT
  - Only airborne pathways are considered (including deposition onto, and then the subsequent ingestion of, plants)
- Event Time: Year 2400
- Peak Dose: 0 y after event (year 2400)

As shown in Table 8-14, the maximum dose due to airborne emissions is 0.0017 mSv/y, which is a small fraction of the regulatory dose limit of 1 mSv/y and the dose constraint of 0.3 mSv/y. Also, the comparison with the maximum dose due to the waterborne emissions, indicates that the impact of airborne emission on humans is negligible, less than 1 % of the impact of the waterborne emissions for the cases considered.

Table 8-14 Dose to Hypothetical Groups Exposed to Airborne Emissions

Location of PCGs	Adult			Ten year old children			One year old infant		
	Dose (mSv/y)	Ratio of criterion of 1 mSv/y	Ratio of criterion of 0.3 mSv/y	Dose (mSv/y)	Ratio of criterion of 1 mSv/y	Ratio of criterion of 0.3 mSv/y	Dose (mSv/y)	Ratio of criterion of 1 mSv/y	Ratio of criterion of 0.3 mSv/y
Balmer Bay	1.6E-03	1.6E-03	5.2E-03	1.7E-03	1.7E-03	5.6E-03	1.4E-03	1.4E-03	4.6E-03
Chalk River	1.6E-03	1.6E-03	5.2E-03	1.5E-03	1.5E-03	5.1E-03	1.4E-03	1.4E-03	4.5E-03
Deep River	1.5E-03	1.5E-03	4.9E-03	1.6E-03	1.6E-03	5.3E-03	1.3E-03	1.3E-03	4.5E-03
Mountain view	1.4E-03	1.4E-03	4.6E-03	1.5E-03	1.5E-03	5.0E-03	1.3E-03	1.3E-03	4.2E-03

Note: Ratios above 1 (i.e. dose exceeds criterion) are shown in **Bold** and shaded.

8.8.1.3 Normal Sensitivity Case 3 – Lower Distribution Coefficients

The purpose of this sensitivity study is to investigate the impact of lower distribution coefficient (k_d) on the dose to humans. According to this scenario, the aquifer and sediment distribution coefficients of each radionuclide of concern are reduced to 50% of the value used in the base case. All other parameters are the same as for normal evolution. It is important to note that any larger variations in k_d are bounded by the bathtub scenario. This is because the bathtub scenario assumes direct transportation of the contaminated water to Perch Creek, bypassing the groundwater system. This is equivalent to ignoring the retarding properties of groundwater transportation (i.e. k_d=1).

This scenario is summarized as follows:

- Based on:
  - Normal Evolution – Leaching Through the Liner
- Primary Difference:
  - Geosphere Kd values were set to half their original values
- Waste Considered:
  - Total Inventory (Table 8-2)
  - Located within the ECM
- Pathways Analysis:
  - Unchanged from Normal Evolution – Leaching Through the Liner
  - Conducted using IMPACT
  - All pathways are considered
  - Fish ingestion is from the Ottawa River
- Event Time: Year 2400
- Peak Dose: 72 y after event (year 2472)

As shown in Table 8-15, doses to PCGs of concern are similar to those for the Normal Evolution Leaching scenario, in the range of 6.8 E-7 mSv/y to 1.7E-4 mSv/y. The estimated doses are a small fraction of the regulatory dose limit of 1 mSv/y and the dose constraint of 0.3 mSv/y.

Table 8-15 Doses to Human due to the use of Reduced Distribution Coefficient (kd)

Location of PCGs	Adult			Ten year old children			One year old infant		
	Dose (mSv/y)	Ratio of criterion of 1 mSv/y	Ratio of criterion of 0.3 mSv/y	Dose (mSv/y)	Ratio of criterion of 1 mSv/y	Ratio of criterion of 0.3 mSv/y	Dose (mSv/y)	Ratio of criterion of 1 mSv/y	Ratio of criterion of 0.3 mSv/y
Cottager	6.9E-07	6.9E-07	2.3E-06	6.8E-07	6.8E-07	2.3E-06	7.5E-07	7.5E-07	2.5E-06
Pembroke	5.2E-05	5.2E-05	1.7E-04	9.3E-05	9.3E-05	3.1E-04	1.7E-04	1.7E-04	5.8E-04
Petawawa	4.9E-05	4.9E-05	1.6E-04	9.2E-05	9.2E-05	3.1E-04	1.7E-04	1.7E-04	5.8E-04
Laurentian Valley	4.7E-05	4.7E-05	1.6E-04	8.9E-05	8.9E-05	3.0E-04	1.7E-04	1.7E-04	5.8E-04

Note: Ratios above 1 (i.e. dose exceeds criterion) are shown in **Bold** and shaded.

8.8.1.4 Normal Sensitivity Case 4 – Dust from Dried Perch Creek Bed

The purpose of this sensitivity study is to investigate the impact of dust being released from the bed of Perch Creek, assuming it dried up.

For this assessment, it has been assumed that Perch Creek has completely dried up, allowing for the creek sediment to be suspended, and subsequently inhaled. For this assessment, the concentrations in the creek sediment were taken, at 3 times, converted to a dry "soil" concentration, and suspended in the air. Members of the public were assumed to stand directly in the cloud of dust, thereby ignoring the air dispersion beyond the initial location, and maximizing dose.

This scenario is summarized as follows:

- Based on:
  - N/A – this is a unique case
- Primary Difference:
  - This assessment looks at the effects of someone inhaling the sediment from perch creek in the event that it dries up
- Waste Considered:
  - The sediment concentration in Perch Creek were used as the source term for resuspension
- Pathways Analysis:
  - Only considers inhalation (including volatiles like H-3, C-14, and Radon from Ra-226)
- Event Time:
  - Calculated at years 2900, 3400 and 12400
- Peak Dose: year 2408

Table 8-16 shows the dose from inhalation and from immersion in the cloud, as well as the total dose received by a person standing in the cloud of dust. These doses are extremely low, and do not contribute to the person's total dose in any significant manner.

Table 8-16 Dose from airborne Perch Creek sediment

Year	2900	3400	12400
Inhalation Dose (mSv/h)	4.37E-25	3.07E-25	3.68E-27
Immersion Dose (mSv/h)	6.20E-31	4.35E-31	4.07E-33
Total Dose (mSv/h)	4.37E-25	3.07E-25	3.92E-27

8.8.2 Sensitivity Study for Human Intrusion

The following cases perform sensitivity analysis with respect to the main HI case presented in Section 8.6.1.

8.8.2.1 H.I. Sensitivity Case 1 – Acute – Larger Diameter Well

The purpose of this study is to investigate the impact of drilling a larger diameter well, on the driller.

Under this scenario, the depth of the well remains at 30 m but the diameter of the well is increased to 1.2 m, compared with the 0.2 m well assessed for the base case. This will result in more material being brought to the surface, and will require longer to drill. It is assumed that the work will be carried out immediately after Institutional Control and that it will take 48 hours to be completed, compared with 24 hours for the 0.2 m well. As with the base case, the drill is assumed to disturb an area where a particular waste stream is disposed. Therefore, a higher-concentration inventory is considered as defined in Table 8-3. Furthermore, as with the base case, the drill is assumed to not deflect or stop, and the driller is assumed to not recognize that something is wrong and stop.

This scenario is summarized as follows:

- Based on:
  - H.I. Main – Acute Exposure from Well Drilling
- Primary difference:
  - Well diameter is 1.2 m, as opposed to 0.2 m (thereby increasing the amount of material that is brought to the surface
  - The drilling is assumed to take twice as long (48h vs 24 h originally)
- Waste Considered:
  - Bunker Inventory (Table 8-3)
    - The amount of waste brought to the surface was estimated (using well dimensions) and was diluted by the clean material also brought up by drill.
    - The waste is spread over 2200 m^2
- Pathways Analysis:
  - Soil ingestion, radon, inhalation and external gamma
  - Additionally, the inhalation and radon pathways from the remaining buried waste (still in the ECM), represented by the Total Inventory (Table 8-2), are calculated.
- Event Time: Year 2400
- Peak Dose: N/A – this is an acute dose

Dose to drilling workers due to acute exposure, is estimated to be 0.11 mSv, about 17 times the dose that workers are calculated to receive while drilling the smaller 0.2 m well. The key radionuclide is Nb-94, and the primary pathway is external exposure to contaminants, which are not the same as the small well scenario.

8.8.2.2 H.I. Sensitivity Case 2 – Chronic – 3 m Basement

The purpose of this study is to determine the effects to the calculated dose received by a member of the public caused by the addition of a 3 m deep basement to the H.I. Main – Chronic Exposure from Living on ECM case. The primary changes to the dose received will be due to increased radon ingress into the house, increased concentration in the soil around the farming area (caused by spreading a larger amount of excavated soil), and the dose associated with the physical digging of the basement. Two receptors are considered for this assessment. The first is the farmer, who will live in the house with the 3 m basement, on top of the ECM, as well as farming the contaminated area. The second is the person who digs the foundation out, and is exposed to external and inhalation hazards from digging into the waste.

Under this scenario, the depth of the hypothetical basement was increased from 1 m to 3 m. The digging of a 3 m basement will result some bulk waste being excavated, as the cap is only 2.15 m thick. This excavated waste is assumed to be distributed over the farming and living area, in addition to the waste from the well drilling (see Section 8.6.1). As such, these two wastes have been combined to increase the total activity present as surface waste.

- The waste excavated from the drilling of the well is assumed to be Bunker Waste (Table 8-3), consistent with H.I. Main – Chronic Exposure from Living on ECM
- The waste excavated by digging the basement is as follows: Given that the lowest activity wastes will be placed at the top of the ECM, to act as shielding, the **0.85 m of waste that is intercepted has been represented as equivalent to 1% of the activity concentration of the Total Waste inventory (Total Waste inventory is shown in Table 8-2)**.

The farmer is assessed in the same manner used for the H.I. Main – Chronic case, with the exception of the basement depth, and the increased surface waste.

For the person digging the basement, it has been assumed that an excavator will be used, given the size of the basement. However, in order to be conservative, no credit has been taken for the shielding or distance from the waste that would be provided by the excavator, and the worker is treated as standing in the center of the completed basement for the full digging time. This is a conservative assumption, as it maximized the possible dose of the digger. It is assumed that this excavation would take 8 h. during this time, the digger will be exposed to external radiation from the 4 walls of the basement, represented using 1% of the Total Waste inventory as discussed above, and from the floor of the basement, represented using the Total Waste inventory, as this extends down into the ECM.

This scenario is summarized as follows:

- Based on:
  - H.I. Main – Chronic Exposure from Living on ECM
- Primary Difference:
  - Depth of basement is increased from 1 m to 3 m (affects radon ingress only)
  - Results in some extra waste being exhumed, and added to the drilling waste on the surface
  - Dose to the person digging the basement was also calculated separately
- Waste Considered:
  - The waste in the ECM is the Total Inventory (Table 8-2)
    - Unchanged H.I. Main – Chronic Exposure from Living on ECM
  - The waste on the surface is a combination of the waste exhumed from the well (Bunker) (same as H.I. Main – Acute Exposure from Well Drilling and H.I. Main – Chronic Exposure from Living on ECM) and the waste exhumed in the digging of the basement (1% of the Total Inventory)
    - The volume of the waste exhumed by the basement is:
      - 0.85m * 22m *25 m)
      - 0.85 m is the 3 m basement, less 2.15 m of clean cover material
- Pathways Analysis:
  - External gamma, inhalation, ingestion of food from farm (plant, meat, milk) drinking of water from well, incidental soil ingestion, radon, and aquatic food (from perch creek)
    - Fish at a rate of 5.4 kg/y – 0.5 local fraction
    - Crustacea and molluscs at a rate of 0.9 kg/y – 0.5 local fraction
- Event Time: Year 2400
- Peak Dose: 50557 years after event

The peak dose rates for living above the ECM and farming in the contaminated soil is shown in Table 8-17 The results for the H.I. Main – Chronic case have also been presented in order to illustrate the effect of adding the basement. As shown in Figure 8-18 and Figure 8-19, the main dose contributor is Po-210, followed by Ra-226, which together account for 90% of the dose for the 3 m basement case. The major pathway is water ingestion.

Table 8-17 Peak Dose Rates for Chronic Human Intrusion Cases (Human intrusion occurring @ 2400)

	HI Main - Chronic (Peak Dose @ 54218 years after intrusion)	H.I. Sensitivity Case 2 – Chronic – 3 m Basement (Peak Dose @ 50557 years after intrusion)
Dose from ECM (mSv/y)	4.0E-04	6.6E+00
Dose from Surface Waste (mSv/y)	5.4E+00	1.63E-03
Total Maximum Dose Rate (mSv/y)	5.4E+00	6.6E+00

The external dose received from the act of digging the 3 m basement (at year 2400) is expected to be 5.88E-09 mSv, assuming that it takes 8 hours to dig the basement. The dose from dust inhalation during this work is 1.62E-05 mSv. This results in a total dose for the person digging the basement of 1.62E-05 mSv, which is very low.

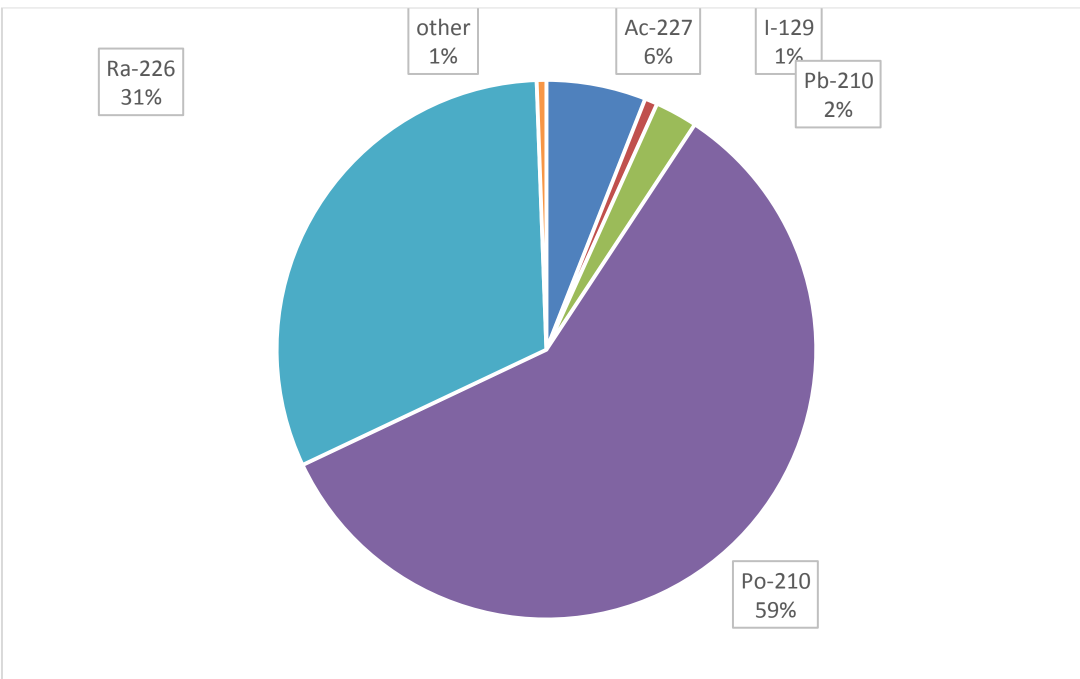

Figure 8-18 Percent Contribution by Radionuclide for Peak Dose to Farming Residents (H.I. Sensitivity Case 2 – Chronic – 3 m Basement)

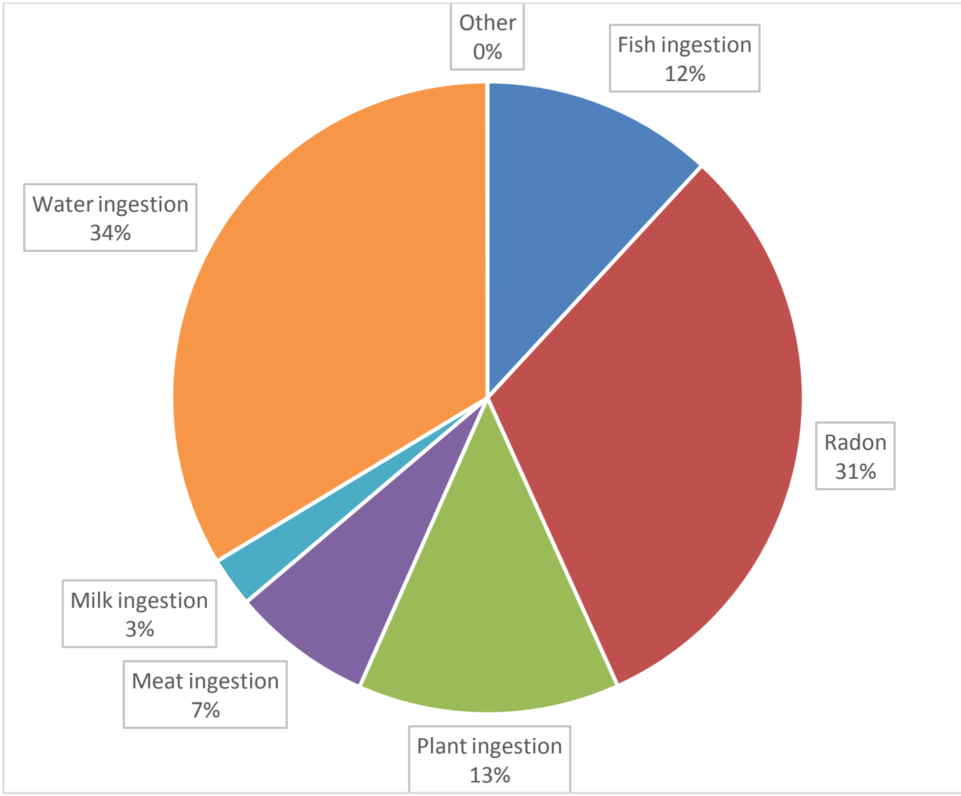

Figure 8-19 Percent Contribution by Pathway for Peak Dose to Farming Residents (H.I. Sensitivity Case 2 – Chronic – 3 m Basement)

8.8.3 Sensitivity of Human Intrusion Scenarios to Intrusion Event Time

The following cases perform sensitivity analysis with respect to the main HI case presented in Section 8.6.1 and the sensitivity study for HI presented in Section.8.8.2, assuming human intrusion occurs in the years 2200 and 2300, i.e. 100 and 200 years from closure. All parameters, pathways, and other features of the cases are unchanged, with the exception of the initial source term, which is modified to reflect the different intrusion time.

8.8.3.1 Time Sensitivity Case 1 – H.I. Main – Acute Exposure from Well Drilling

This scenario assesses the sensitivity of the H.I. Main – Acute Exposure from Well Drilling case (drilling bunker waste) to the time of intrusion. The diameter of the well is unchanged, at 0.2 m, as presented in Section 8.6.1 and it is assumed that the work will be carried out in the years 2200 and 2300 respectively. The estimated acute doses to the driller are shown in Table 8-18, for the base case (Year 2400) and for the years 2200 and 2300.

Table 8-18 Acute Dose for Driller (0.2 m diameter well)

Year HI Occurs	Total dose (mSv)
2200	2.5E-02
2300	8.8E-03
2400 (Base Case)	6.4E-03

The estimated dose to the driller is 2.5E-2 mSv and 8.8E-03 mSv for human intrusion occurring in years 2200 and 2300 respectively. Though higher than the base case, the higher acute dose for year 2200 represents only 2.5% of the lower intrusion dose benchmark of 1 mSv/y. As shown in Figure 8-20, the major dose contributor is Cs-137 (85%) for year 2200 and the percent contribution decreases to 3% in year 2400. Contributions of Nb-94 and Am-241 increase from 6% and 2% respectively in year 2200 to 23% and 49% in year 2400. Similar shifts are also noted for the major pathway (Figure 8-21). The key pathway is external exposure to contaminants (85%) in year 2200, however, the major pathway for year 2400 is inhalation (47%) with percent contribution of external exposure decreased to 30%.

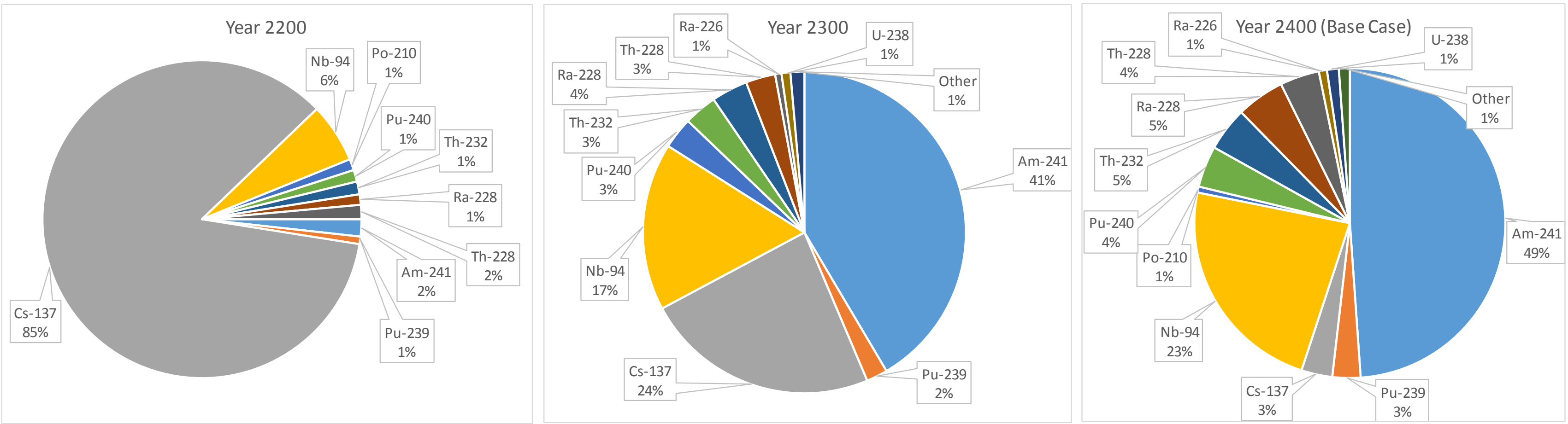

Figure 8-20 Percent Contribution by Radionuclide for Maximum Dose to Driller for Different Intrusion Event Time

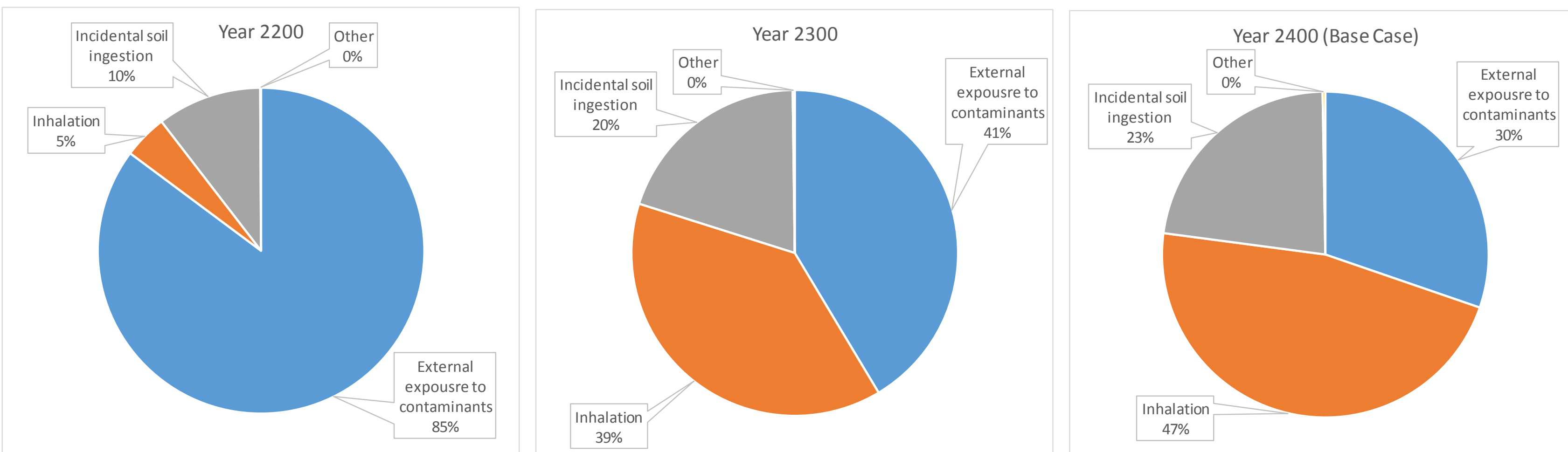

Figure 8-21 Percent Contribution by Pathway for Maximum Dose to Driller for Different Intrusion Event Time

8.8.3.2 Time Sensitivity Case 2 – H.I. Main – Chronic Exposure from Living on ECM

This case assesses the sensitivity of the H.I. Main – Chronic Exposure from Living on ECM case, to the time of human intrusion. This chronic scenario involves intrusion into the waste while inhabiting a dwelling on top of the ECM, using a residential well that abstracts undiluted leachate and farming in a mixture of exhumed waste (from the drilling of the well) and garden soil, as presented in Section 8.6.1. It is assumed that the event will occur in years 2200 and 2300 respectively, and the doses are assessed from this point onwards. The estimated chronic doses to the farming residents are shown in Table 8-19, for the base case (Year 2400) and for the years 2200 and 2300. Percent contribution by radionuclide and by pathway are presented in Figure 8-22 and Figure 8-23 respectively. The estimated doses to the farmer are shown in Table 8-19, for the base year (Year 2400) and for the years 2200 and 2300.

Table 8-19 Peak Dose for Farming Residents

Year HI Occurs	Time of Peak Dose (Years after HI)	Dose from ECM (mSv/y)	Dose from Surface Waste (mSv/y)	Total Peak dose (mSv/y)
2200	54218	5.4E+00	4.0E-04	5.4E+00
2300	54218	5.4E+00	4.0E-04	5.4E+00
2400 (Base Year)	54218	5.4E+00	4.0E-04	5.4E+00

As shown in Table 8-19, the peak is reached approximately 54200 years after human intrusion event occurred and the estimated doses are essentially the same for all three scenarios. Similar results are noted in Figure 8-22 and Figure 8-23. The main dose contributor is Po-210 and, and the key pathways are ingestion of food and water. The predicted exposure levels exceed the lower benchmark of 1 mSv/y but are still below the upper dose benchmark of 20 mSv/y for human intrusion (see Section 2.4).

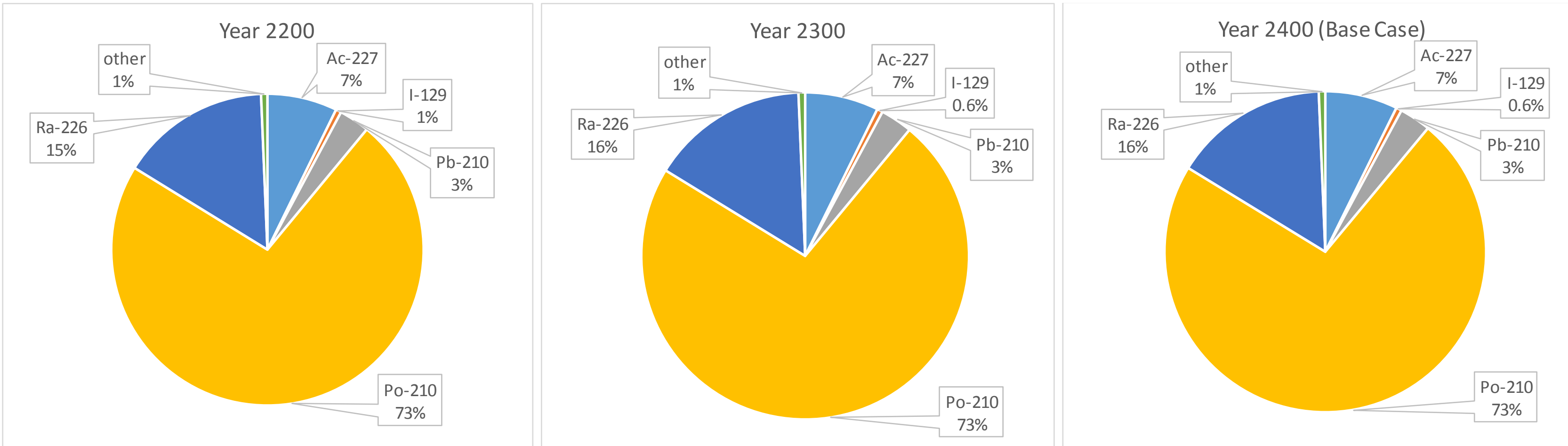

Figure 8-22 Percent Contribution by Radionuclide for Peak Dose to Farming Residents with Different Intrusion Event Time

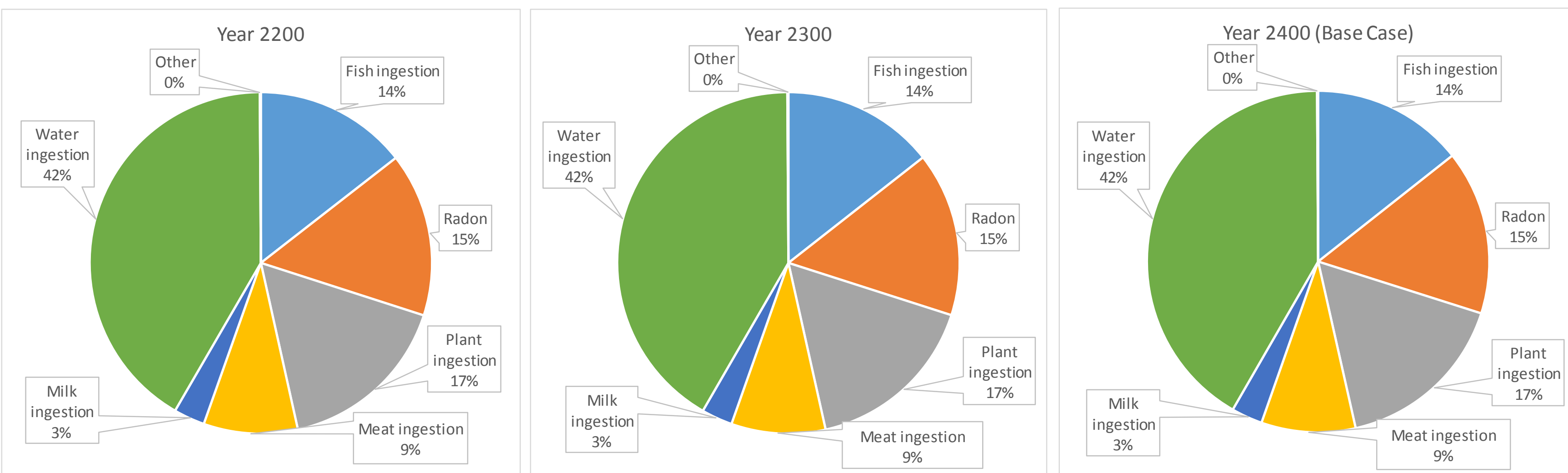

Figure 8-23 Percent Contribution by Pathway for Peak Dose to Farming Residents with Different Intrusion Event Time

8.8.3.3 Time Sensitivity Case 3 – Larger Diameter Well

This scenario assesses the sensitivity of the H.I. Sensitivity Case 1 – Acute – Larger Diameter Well case to the time of intrusion. The diameter of the well is 1.2 m, consistent with the H.I. Sensitivity Case 1 – Acute – Larger Diameter Well case, as presented in Section 8.8.2.1 and it is assumed that the work will be carried out in the years 2200 and 2300 respectively. The estimated acute doses to the driller are shown in Table 8-20, for the base year (Year 2400) and for the years 2200 and 2300.

Table 8-20 Acute Dose for Driller (1.2 m diameter well)

Year HI Occurs	Total dose (mSv/y)
2200	1.4E+00
2300	2.3E-01
2400 (Base Year)	1.1E-01

The estimated dose to the driller is 1.4 mSv and 0.23 mSv for human intrusion occurring in years 2200 and 2300 respectively. Similar to the small well scenario, these are higher than the dose estimated for year 2400. The higher dose for year 2200 exceeds the lower intrusion dose benchmark of 1 mSv/y but it is still below the upper dose benchmark of 20 mSv/y for human intrusion (see Section 2.4). As shown in Figure 8-24, the major dose contributor is Cs-137 (93%) for year 2200 and the percent contribution decreases to 12% for year 2400. Contributions of Nb-94 and Am-241 increase from 5% and 1% respectively in year 2200 to 68% and 7% in year 2400. External exposure is the key pathway for all three intrusion event times, from 91% for year 2400 to 99% for year 2200.

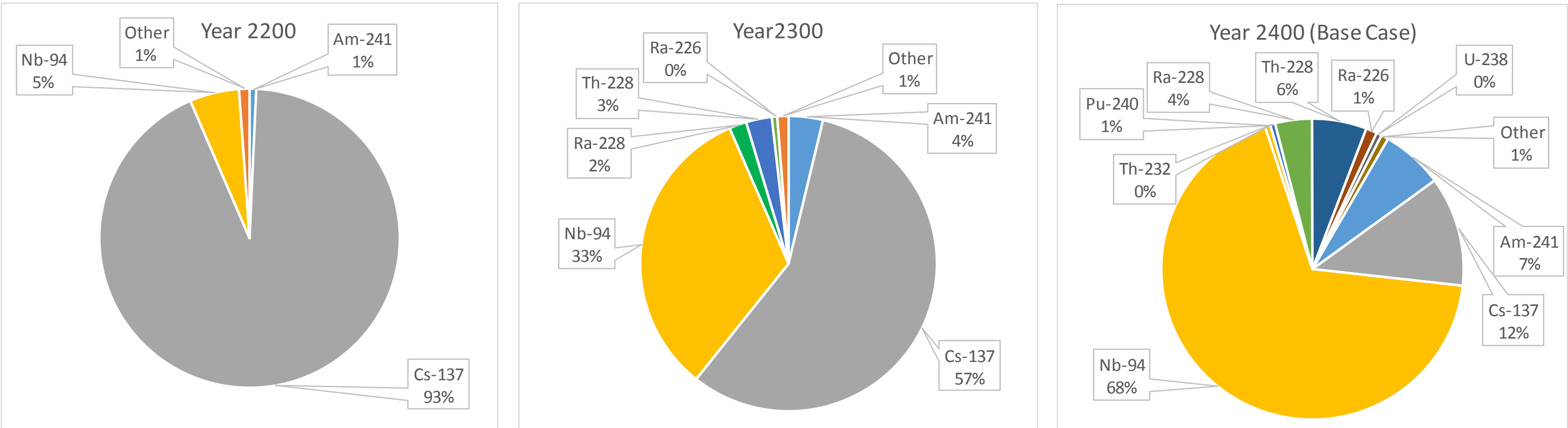

Figure 8-24 Percent Contribution by Radionuclide for Maximum Dose to Driller for Different Intrusion Event Time (Larger Well Scenario)

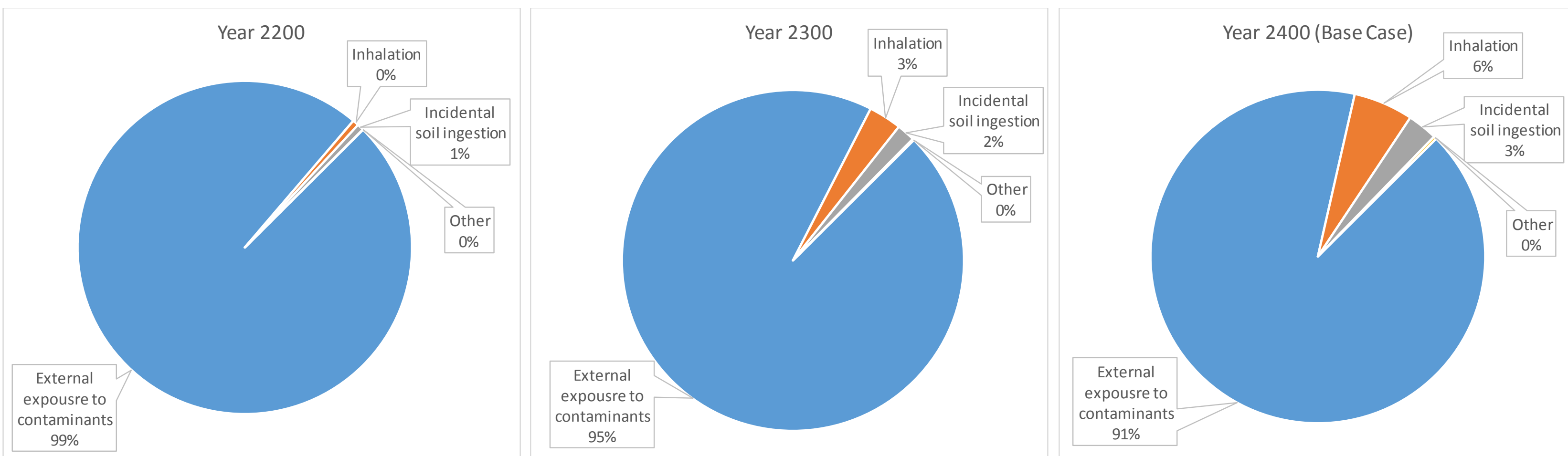

Figure 8-25 Percent Contribution by Pathway for Maximum Dose to Driller for Different Intrusion Event Time (Larger Well Scenario)

8.8.3.4 Time Sensitivity Case 4 –3 m Basement

This case assesses the sensitivity of H.I. Sensitivity Case 2 – Chronic – 3 m Basement, to the time of human intrusion. This chronic scenario involves intrusion into the waste while inhabiting a dwelling on top of the ECM that has a 3 m basement. The farmer is still assumed to be using a residential well that abstracts undiluted leachate and farming in a mixture of exhumed waste (from the drilling of the well and from the digging of the basement) and garden soil, as presented in Section 8.8.2.2. It is assumed that the event will occur in years 2200 and 2300 respectively, and the doses are assessed from this point onwards. The estimated chronic doses to the farming residents are shown in Table 8-19, for the base case (Year 2400) and for the years 2200 and 2300. Percent contribution by radionuclide and by pathway are presented in Figure 8-26 and Figure 8-27 respectively. The estimated doses to the farmer are shown in Table 8-21, for the base year (Year 2400) and for the years 2200 and 2300.

Table 8-21 Peak Dose for Farming Residents

Year HI Occurs	Time of Peak Dose (Years after HI)	Dose from ECM (mSv/y)	Dose from Surface Waste (mSv/y)	Total Peak dose (mSv/y)
2200	0	2.9	17.7	**20.6**
2250	0	2.7	5.9	8.6
2300	50577	6.6	1.6E-03	6.6
2400 (Base Year)	50577	6.6	1.6E-03	6.6

As shown in Table 8-19, the peak dose is reached at year 0 (i.e. at the time of the event, rather than in future years). The highest dose is 20.6 mSv, observed from the 2200 case, which slightly exceeds the 20 mSv/yr upper dose benchmark of 20 mSv/y for human intrusion. The main dose contributor is Cs-137, and the key pathway is external dose.

The following paragraphs present a few points regarding the conservatism and incredibility of this scenario:

(1) Waste activity concentrations at the top level of the waste.

According to the Waste Placement and Compaction Plan [8-23]

"When possible, wastes with higher dose rates are placed in the lower portions of the disposal cells and covered with waste having lower dose rates or fill materials to provide shielding from radiation….and…Waste placement will allow for placement of waste exhibiting high radiation levels only on a scheduled basis to maintain ALARA conditions associated with cell operations."

As discussed in Section 8.8.2.2, for the purposes of this scenario, we have assumed that the top 1m of waste will have concentrations that do not exceed 1% of the total inventory concentrations. This assumption will need to be evaluated as part of a sensitivity analysis on the inventory, once conservatism in the inventory estimates are documented.

(2) Low probability of inadvertent human intrusion in the near future.

Institutional memory is expected to be high at early times after the institutional control period. It would significantly reduce the intrusion probability and thus the risk associated with this hypothetical scenario.

(3) Cs-137.

It should be noted that the dominating radionuclide at 2200 is Cs-137 which has a relatively short half-life (30.17 years). Its activity is therefore fast decaying and e.g. by 2250, the peak dose is well below 20 mSv/y, as shown in Table 8-21, Figure 8-26, and Figure 8-27. Furthermore, much of the Cs-137 inventory would be emplaced in High Integrity Containers. The simple and conservative model used in this stage of the assessment does not take credit for the barrier function of these containers

(4) Digging a well: A “what if” scenario

Some of the dose to the intruder is from consuming well water. Removal of this contribution to the dose will result in a dose that is less than 20mSv/yr. However, many residents in the area use river water, and those residences that use well water typically drill to a deep aquifer that is not expected to be affected by the facility.

Based on this result, and in spite of the very low probability associated with this hypothetical scenario, the PA recommends that one or more of the following measures be considered, as appropriate:

1. Assess the probability of well water use in this area;
2. Confirm the conservatism in the Cs-137 inventory; and,
3. No credit is taken for waste stabilization and packaging in the RESRAD postclosure calculations. A more robust PA performed using modelling tools that can incorporate these characteristics could be explored. Such an analysis will require information on the various waste forms and packaging properties. Stabilization and packaging is expected to significantly slow down the release of Cs-137 and hence allow for additional decay and lower environmental concentrations.

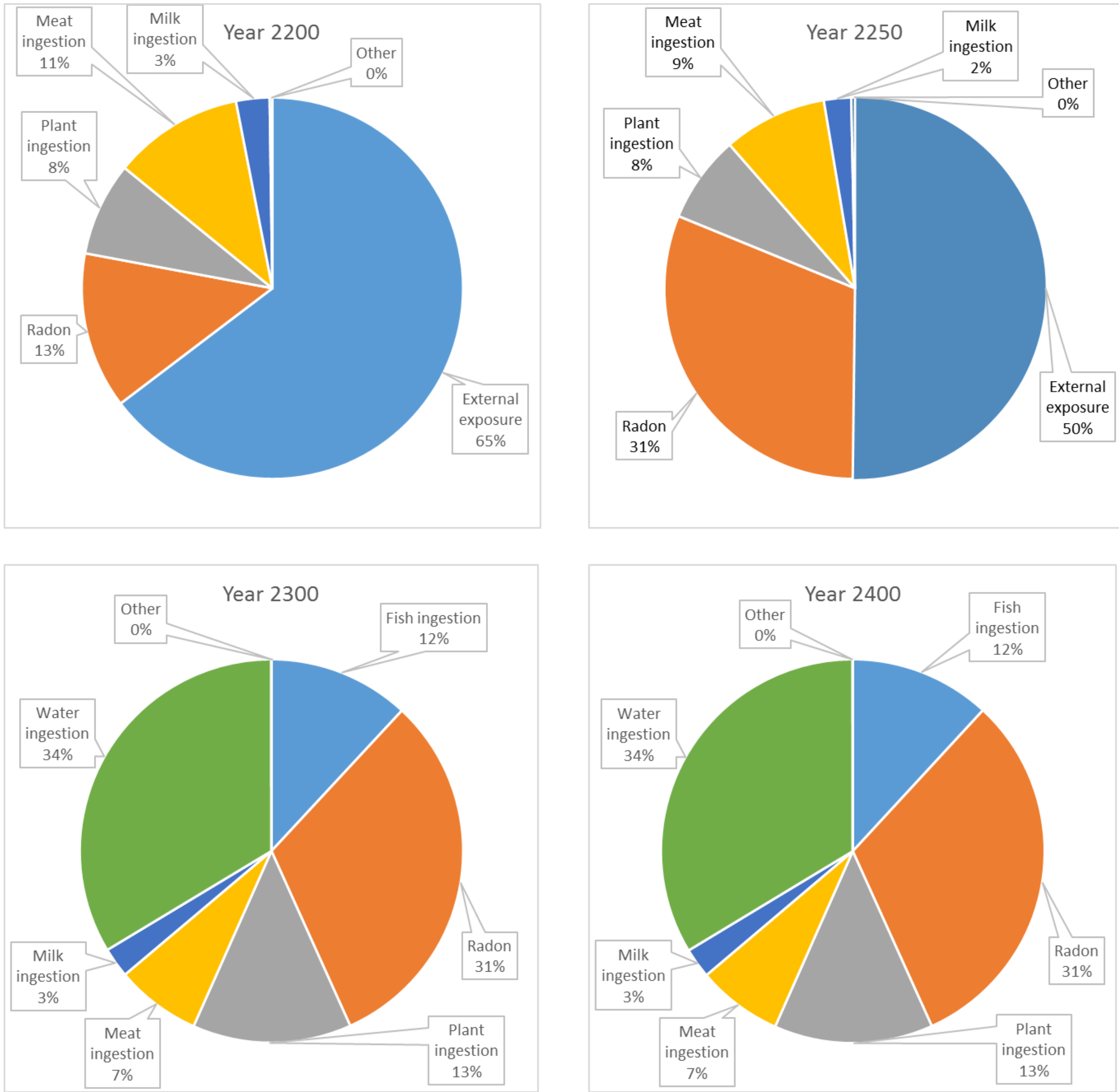

Figure 8-26 Percent Contribution by Radionuclide for Maximum Dose for Different Intrusion Event Time (3m Basement Scenario)

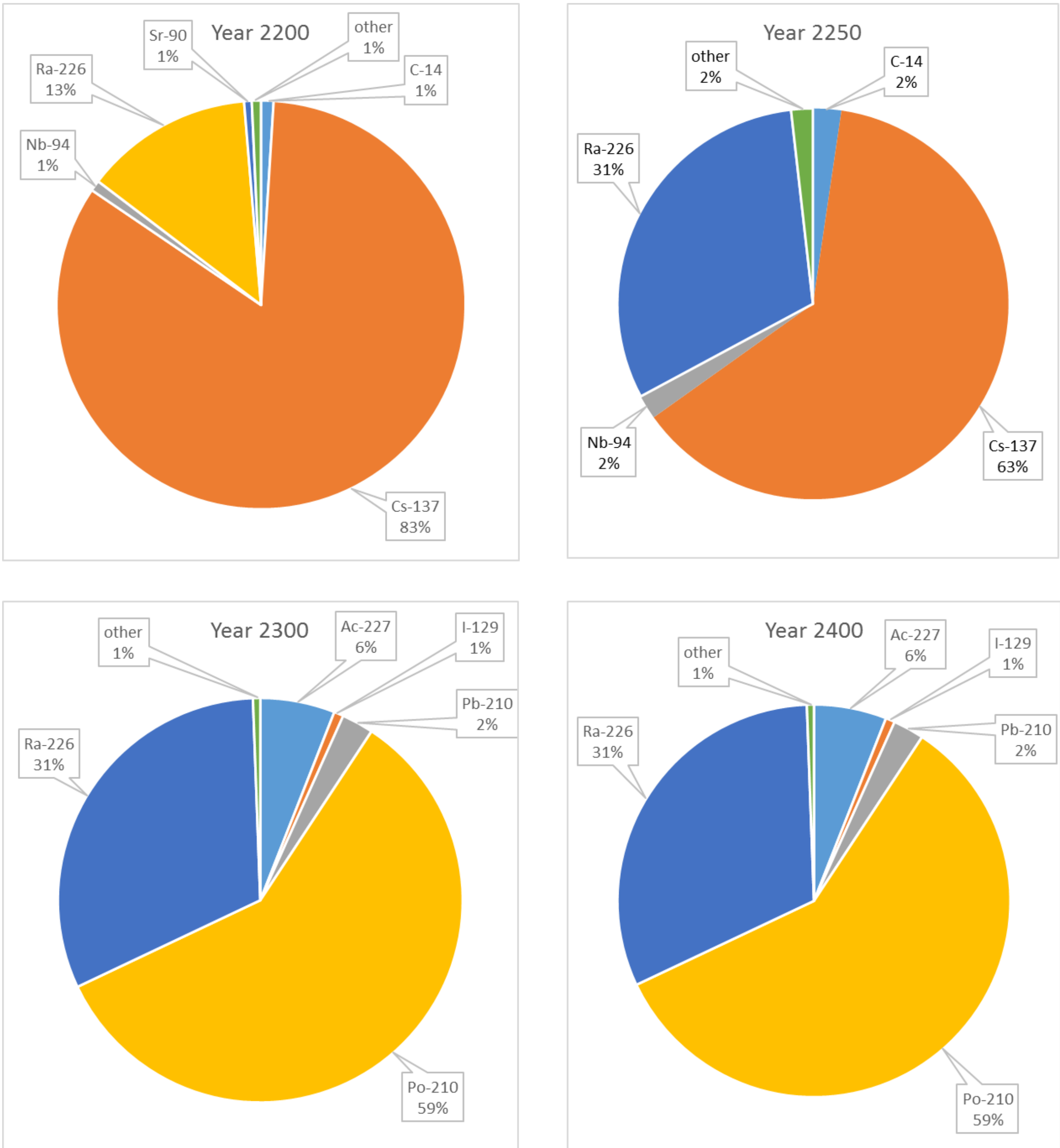

Figure 8-27 Percent Contribution by Pathway for Maximum Dose for Different Intrusion Event Time (3m Basement Scenario)

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9. OPERATIONAL PROGRAMS

Operational aspects relevant to safety during pre-closure include Health, Safety, Security, and Environment (HSSE) Programs, conduct of operations, operating limits and conditions, and criticality safety.

9.1 Health Safety Security and Environment Programs

Canadian Nuclear Laboratories has established 12 HSSE programs "to ensure that CNL operates in full compliance with statutory and legislative requirements, while promoting and supporting performance excellence underpinned by a strong safety culture" [9-1]. "Assuring safety at CNL encompasses nuclear safety, as well as the broader HSSE landscape including operations, maintenance, chemistry, engineering, operating experience, human performance, RP, OSH, fire protection, environmental protection, security and emergency preparedness" [9-1]. "Combining a strong safety culture (human behaviour) and effective safety management (processes and oversight) prevents events and assures the safety and security of people, facilities and the environment during normal and upset conditions" [9-1].

The HSSE programs are in accordance with the principles of defence-in-depth and QA, and include:

- Radiation Protection and Dosimetry.
- Emergency Preparedness.
- Environmental Protection.
- Fire Protection.
- Nuclear Criticality Safety.
- Nuclear Materials and Safeguards.
- Occupational Safety and Health.
- Operating Experience.
- Physical Security.
- Pressure Boundary.
- Transportation of Dangerous Goods.
- Waste Management.

9.2 Radiation Protection and Dosimetry

Canadian Nuclear Laboratories RP Program is designed and implemented to ensure that CNL complies with, or exceeds, the level of radiation safety that is required by the relevant regulations pursuant to the NSCA and CNL's Health and Safety Policy.

The RP and Dosimetry program [9-2], complies with CNL RP requirements [9-3], as well as RP regulations [9-4]. Canadian Nuclear Laboratories applies the ALARA principle in all activities involving the use of ionizing radiation. All radiation doses to personnel or members of the public must be justified, in accordance with the ALARA principle and be maintained below regulatory limits.

The fundamental objectives of the CNL's RP Program are to:

- Limit the doses to less than the regulatory limits.
- Limit doses to employees and members of the public to levels ALARA, social and economic factors being taken into account (ALARA principle).
- Prevent detrimental non-stochastic (deterministic) health effects caused in employees and members of the public by CNL's use of radiation.

At all CRL facilities, these objectives are achieved through facility design, internal and external dosimetry programs, staff training, administrative exposure control procedures, contamination control requirements, and work planning and supervision.

Canadian Nuclear Laboratories Work Permit System is used to ensure that potential hazards (such as Radiation hazards), are properly identified before work begins, and that work is conducted in a safe manner. Radiation exposure within the NSDF and any release of radioactive material from the NSDF and its associated operation activities, shall be kept ALARA. Any radiation exposure shall be below the established regulatory limits. These dose limits are prescribed for normal operations, although provisions must be in place to mitigate the potential exposure resulting from an accident.

Compliance with the NSCA ensures appropriate RP is optimised within dose constraints and provides a system of dose limitation.

The ICRP recommendations are followed where required. The regulatory dose limits for normal operations are stated in Section Definition of Safety Objective and Safety Criteria.

The ALARA principle is applicable to justifying risks from radiological hazards during routine operation. Canadian Nuclear Laboratories ALARA program, as give in [9-2] shall be followed. The essential elements of ALARA [9-5] are:

- Demonstrated management commitment to the ALARA principle.
- Implementation of ALARA through design, organization and management, selection and training of personnel, oversight of the RP program, resources, and documentation.
- Establishment of nuclear safety culture.
- Planning and control of non-routine work.
- Application of task-specific dose and dose-rate radiological control hold points.
- Performance of regular operational reviews.

The ALARA principle in the NSDF will be achieved by:

- Implementing zoning and access control measures.
- Providing adequate shielding for structures and waste packages with high radiation fields.
- Providing process equipment segregation.

- Radiation alarms in place.
- Continuous monitoring.
- Improvement of waste stream processing.
- Work assessment and planning for unusual and/or high hazard tasks.
- Post-job ALARA review.
- Training.
- Approved procedures.

Further reduction in operating staff doses is achieved by minimizing releases through periodic inspection and preventive maintenance of equipment.

Protective measures against the hazards of ionizing radiation, will be considered to be optimized when further reductions in radiation doses are outweighed by the additional efforts and costs required for their implementation. This principle applies to all phases throughout the life cycle of a facility, from design to decommissioning, and will be a particularly important consideration when developing the operational procedures.

Dosimetry is a necessary component of the program, providing a quantitative measure of the effectiveness of the radiation safety program as it applies to both the individual worker and the collective workforce. Dosimetry is a fundamental requirement for the demonstration of compliance with regulatory obligations mandated by the site license.

9.3 Emergency Preparedness

The Emergency Preparedness performance objectives, criteria and requirements are detailed in the CNL company-wide Emergency Preparedness Program [9-6]. This program uses the following performance measures to assess site-wide compliance with program requirements:

- Emergency procedures are reviewed annually and revised as required.
- Designated personnel are trained in their emergency response duties.
- Facility or building personnel conduct and/or participate in drills and exercises, as identified in the annual exercise schedule.
- Emergency equipment is maintained in a state of readiness and quality confirmation is reported to the Emergency Preparedness Office.

9.4 Environmental Protection

The Environmental Management system [9-1] at CNL, provides an overview of the key processes, organizational structure and the responsibilities associated with the Environmental Protection program [9-7]. An index to documentation [9-1] lists the policy, requirements documents and all supporting and implementation procedural documents for environmental protection. Operations and activities conducted at CNL sites in Canada are bound by environmental requirements specified in the:

- Nuclear Safety and Control Act [9-8].
- Canadian Environmental Protection Act [9-9].
- Canadian Environmental Assessment Act [9-10].
- Fisheries Act [9-11].
- Transportation of Dangerous Goods Act [9-12].
- Species at Risk Act [9-13].

9.5 Fire Protection

The objectives of the Fire Protection program [9-14] are:

- Protect life and provide fire safety.
- Prevent fire losses and degradation of fire protection coverage.
- Provide responsible fire protection and change control that enhances fire protection.
- Demonstrate compliance to applicable fire protection codes and standards.
- Improve fitness for purpose, with respect to fire protection.
- Provide reliable facilities from a fire protection perspective.
- Improve business performance and provide risk management using various tools such as self-assessment, fire protection screening process and fire hazard analysis.

9.6 Nuclear Criticality Safety

Nuclear criticality safety protects against the consequences of a criticality accident, preferably by preventing such an accident altogether. The CNL Nuclear Criticality Safety program [9-15] complies with the CNSC Regulatory Document RD-327 [9-16], which provides requirements for the prevention of criticality accidents in the handling, storage, processing, and transportation of fissionable materials, and the long-term management of nuclear waste.

9.7 Nuclear Materials and Safeguards

The Nuclear Materials and Safeguards Management program [9-17], provides an overview of the governance for the management of nuclear materials and safeguards-related activities. The program describes the laws, regulations and organizational structure of the Nuclear Materials and Safeguards Management. Nuclear Materials and Safeguards Management applies to all activities involving the procurement and receipt of radioisotopes and radiation sources, as well as the procurement, receipt, disposition, transfer, accounting, safeguards management, storage and inventory management of nuclear materials, as identified in applicable laws and standards [9-17].

The Integrated Safeguards Approach for CNL facilities with static spent dry fuel storage [9-18], provides guidance to CNL staff to facilitate IAEA integrated safeguards inspections and design information verification. This document describes requirements, responsibilities and processes for the safeguards inspections performed by the IAEA, including:

- Short notice random inspection.
- Physical inventory verification.

9.8 Occupational Safety and Health

The CNL employee health and safety policy is defined by the OSH program [9-19]. This program ensures that a safe and healthy work environment is maintained at CNL facilities, minimizing losses associated with hazardous conditions, accidents and injuries in the workplace [9-19]. The OSH program specifies the procedures, supporting documents, records and forms, and training needed to effectively realize the OSH objectives [9-19]. This program complies with applicable Federal and Provincial occupational health and safety legislation, regulations and standards.

The OSH program requirements [9-20], were established as a result of a cooperative effort amongst various company-wide programs, such as:

- Radiation Protection.
- Fire Protection.
- Operational Experience.
- Security.
- Radioactive Material Transportation.
- Environmental Protection.
- Organizational Development and Training.

9.9 Operating Experience

The Operating Experience program [9-21], uses information from within CNL and from the nuclear industry to improve the safety of operations, improve operational performance, and reduce the significance and the occurrence of unplanned events at CNL sites in Canada. The unplanned events reported to OPEX are entered into a database of operating experiences that are monitored for trends and used to share any lessons learned.

The OPEX program provides processes for the identification and investigation of unplanned events, determination of corrective actions, internal notification to stakeholders, and trending information sharing – both internally and with the broader nuclear industry.

9.9.1 Human Performance

The Human Performance program [9-22] assists managers to anticipate, manage and monitor the effects of variability in human performance on organizational outcomes. The objectives of the Human Performance program [9-22] are:

- Improve management's understanding of the effect of human performance on event rates, as part of CNL's overall approach to risk management.
- Aid management in reducing the frequency and severity of adverse events resulting from human error.

- Support employees in recognizing error-likely circumstances and in applying measures at the task and task step level to reduce the likelihood of significant events resulting from error.
- Meet human performance related licensing requirements and World Association of Nuclear Operators performance objectives.
- Assist CNL in achieving and sustaining a strong organizational safety culture.

9.10 Physical Security

Security is responsible for implementing the Treasury Board Secretariat Policy on Government Security unilaterally across CNL, including the requirements of the Nuclear Security Regulations [9-23]. The objective of the Corporate Security Program is to adhere to the regulatory requirements and company policies, while providing efficient customer service to support the priorities of a business environment.

The Physical Security program implements CNL's Security Policy and requirements at CNL [9-24].

9.11 Pressure Boundary

The Pressure Boundary program [9-25] implemented by CNL ensures that all pressure-retaining systems and components are constructed, operated and maintained in accordance with CSA N285.0 [9-26] and CSA B51 [9-27].

9.12 Transportation of Dangerous Goods

The Transportation of Dangerous Goods Program [9-28], applies to all activities involving the transportation of dangerous goods. The main objectives of the Program are [9-28]:

- To protect persons, property and the environment from the effects of radiation and hazardous material during transport by establishing and maintaining requirements and processes necessary to facilitate the safe transport of dangerous goods to and from CNL sites in accordance with regulatory requirements.
- Ensure compliance with applicable regulatory and licence requirements.

9.13 Waste Management

The Waste Management Program [9-29] describes the requirements and processes for waste management activities at all CNL sites in Canada. These requirements are in compliance with applicable regulatory and licence requirements. The overall objective of the Waste Management Program is to ensure that any activity involving planning for, handling, processing, transporting, storing, or disposing of waste is performed in a manner that protects the workers, public and environment. The Waste Management Program also implements CNL environment [9-30] and health and safety [9-19] policies with regard to waste management.

9.14 References

[9-1] *Management System*, CW-514100-MAN-001, Revision 2, 2014 October.

[9-2] *Radiation Protection*, CW-508740-OV-145, Revision 0, 2011 June.

[9-3] *AECL's Radiation Protection Requirements*, RC-2000-633-0, Revision 2, 2008 October.

[9-4] *Radiation Protection Regulations*, SOR/2000-203.

[9-5] *ALARA Program,* CW-508740-GL-203-01, Revision 0, 2011 May.

[9-6] *Emergency Preparedness*, CW-508730-OV-143, Revision 1, 2012 November.

[9-7] *Environmental Protection Program Documentation*, CW-509200-GDI-101, Revision 7, 2015 August.

[9-8] *Nuclear Safety and Control Act*, c. 9, 1997.

[9-9] *Canadian Environmental Protection Act*, 1999 (S.C. 1999, c. 33).

[9-10] *Canadian Environmental Assessment Act*, (S.C. 1992, c. 37).

[9-11] *Fisheries Act*, (R.S.C., 1985, c. F-14).

[9-12] *Transportation of Dangerous Goods Act*, 1992 (1992, c. 34).

[9-13] *Species at Risk Act*, (S.C. 2002, c. 29).

[9-14] *Fire Protection Program*, 145-508720-OV-001, Revision 0, 2009 February.

[9-15] *Nuclear Criticality Safety*, 145-508720-OV-001, Revision 0, 2009 February.

[9-16] *Nuclear Criticality Safety*, RD-327, CNSC, 2010 December.

[9-17] *Nuclear Materials and Safeguards Management Program*, CW-508510-OV-137, Revision 2, 2013 October.

[9-18] *Integrated Safeguards Approach for AECL Facilities with Static Spent Dry Fuel Storage*, CW-508410-PRO-453, Revision 1, 2010 September

[9-19] *Occupational Safety and Health*, CW-510400-OV-142, Revision 0, 2010 December.

[9-20] *Occupational Safety and Health requirements*, CW-510400-REQ-217, Revision 0, 2010 December.

[9-21] *Operating Experience (OPEX) Program*, CW-508750-OV-125, Revision 1, 2015 April.

[9-22] *Human Performance*, CW-514020-OV-001, Revision 0, 2015 September.

[9-23] *Nuclear Security Regulations*, SOR/2000-209.

[9-24] *Physical Security*, 145-508710-OV-001, Revision 5, 2015 August.

[9-25] *CRL Pressure Boundary Quality Assurance Manual*, CRL-508140-QAM-001, Revision 5, 2015 June.

[9-26] CSA N285.0, *General Requirements for Pressure Retaining Systems and Components in CANDU Nuclear Power Plants/Material Standards for Reactor Components for CANDU Nuclear Power Plants*.

[9-27] CSA B51, *Boiler, Pressure Vessel and Pressure Piping Code*.

[9-28] *Transportation of Dangerous Goods Program*, CW-508520-OV-138, Revision 4, 2015 November.

[9-29] *Waste Management Program Overview*, CW-508600-OV-129, Revision 3, 2015 March.

[9-30] *Environmental Management System for AECL Sites in Canada*, CW-509200-OV-113, Revision 2, 2015 April.

10. CONCLUSION

This PA documents the projected radiological impacts resulting from the NSDF during pre- and post-closure periods. The analysis shows that the site is well characterized and understood and that Safety Objectives can be met. Conventional proven methods and technologies will be used to manage the waste during the operational period. The facility will be operated in compliance with CNL's operational programs. Doses to the public during operations represent a small fraction of regulatory criteria. Doses to non-human biota will be below respective benchmarks. Cumulative effects, taking into account legacy of waste management operations in the area, have been evaluated and the results show that the operation of the NSDF will not result in meaningful changes to the doses to PCG, nor will it result in adverse impacts on ecological health. The post-closure assessment demonstrated that the concept is robust and meets safety objectives for both Normal Evolution and Disruptive scenarios.

10.1 Inventory

The NSDF inventory is represented by operational wastes currently in storage and those that will be generated prior to closure in 2070, which will be dominated by decommissioning and environmental remediation waste streams. The assessed inventory is presented in Section 4. It should be noted that the radiological capacity will also be bounded by the NSDF WAC, which limits the activity of long lived alpha-emitters and beta-gamma emitters to 4,000 Bq/g and 100,000 Bq/g respectively.

The PA provides dose estimates for the waste inventory specified in this report. As the estimated doses all meet the proposed acceptance criteria, there is no additional implication from the PA to the proposed inventory.

10.2 Site

The NSDF will be located on the CRL property, on East Mattawa Road in the Perch Lake Basin, adjacent to Waste Management and LDA. The site is well understood as the conceptual model (as discussed in [10-1]) is underpinned by decades of groundwater monitoring data.

10.3 Design

The design of the NSDF is based on a proven technology which has been in use for decades, applied in both the nuclear industry and in municipal landfills. The technology of waste isolation is mature and well understood. The design incorporates multiple containment features, providing defence in depth to ensure long-term isolation of the waste. The key features include an engineered multilayered cover and base liner. It is planned that the facility will be monitored over a long period of time after closure to demonstrate that the design performs as expected.

The PA shows that the design is adequate for meeting the required safety criteria. One design item that needs re-evaluation is the vents for gas release during the IC period. These vents could provide a pathway for water ingress and release of gases, notably C-14 in the post-closure period. Such a pathway needs to be addressed in the 100% design, the SAR and follow-up addendums as needed.

If a beyond design subsidence event were to occur during the NSDF operations or after closure but prior to the end of Institutional Control, then any potential damage to containment would be repaired or mitigated. However, if such an event were to occur after the end of Institutional Control, it could result in rainwater ingress into the waste and contaminant leaching into the groundwater. Grouting is being considered to address this potential occurrence in the long-term. Grouting is also being considered to address the potential of excessive settlement of waste within the ECM. The PA for grouted wastes is beyond the scope of the current document. It has applications in both pre-closure and post-closure phase of the project.

10.4 Operations

Canadian Nuclear Laboratories has extensive experience in handling the waste streams which will be managed at the NSDF. Current operational programs will ensure that worker doses are below the regulatory criteria and ALARA. This assessment of doses to the public for atmospheric and waterborne pathways, provided an estimate that is a small fraction of both the regulatory limit of 1 mSv/y and CNL's licensing limit of 0.3 mSv/y. Key uncertainties associated with this analysis have been reviewed and indicate high confidence levels in the forecast due to conservatism in the assumptions underpinning the assessment. Several accident scenarios have been considered, which were defined based on a hazard identification and screening analysis. Estimated radiological doses to workers and members of the public meet dose criteria. The SAR will provide further analysis on hazardous scenarios.

10.5 Post-Closure Assessment

A set of conservative Normal Evolution and Disruptive exposure scenarios has been assessed representing different assumptions of the ECM performance after the end of Institutional Control. The exposure scenarios are as follows:

- Normal Evolution – failure of the engineered cover and base liner.
- Normal Evolution – failure of the engineered cover, leading to a "Bathtub" effect.
- Human Intrusion – acute exposure scenario due to drilling of a water well into the waste.
- Human Intrusion – chronic exposure scenario due to an intruder establishing a residence and farming on top of the ECM.
- Glaciation – erosion of the ECM and the resulting loss of containment.
- Seismic event – failure of the cover and partial "spillout" of the waste due to berm failure.

Doses were assessed to PCGs, which were defined based on the current population distribution and present habits and diets. An additional conservatively defined future hypothetical exposure group, was specified as part of the sensitivity analysis.

Analysis of these scenarios shows that the predicted radiological risk to members of the public from the NSDF will not exceed the Safety Criterion of 1 mSv/y for all scenarios, with one exception. Dose to an intruder residing and farming on top of the ECM was estimated to reach a peak of 5 mSv/y, 66000 years after closure. This is a bounding estimate, which conservatively assumes no prior loss of inventory and maximizes quantities of mobile radionuclides available for contaminating drinking water supply at the time of intrusion. The estimated value is below the upper safety criterion for human intrusion, as defined in Section 2.

Comparison with natural analogues, demonstrates that hazardous inventory that will be present within the ECM at the time when glaciations is predicted to occur, will be below inventories currently present within surficial Uranium deposits, which have been proven to be safe for both the environment and the adjacent population centres.

An analysis of the potential radiological effects of the NSDF on non-human biota has shown that risks to non-human biota are also below the relevant benchmarks of 100 μGy/h and 400 μGy/h for terrestrial and aquatic species, respectively.

Sensitivity analyses of these calculations demonstrate the robustness of the NSDF. The NSDF's performance does not rely on any one feature because of the redundant barriers and passive protection provided by the disposal system.

10.6 Compliance with Canadian Nuclear Safety Commission and International Guidance

According to the IAEA Safety Requirements [10-2], the safety objective for a radioactive waste disposal facility is to:

"…site, design, construct, operate and close a disposal facility so that protection after its closure is optimized, social and economic factors being taken into account. A reasonable assurance also has to be provided that doses and risks to members of the public in the long-term will not exceed the dose limit for members of the public and other risk constraints".

Furthermore, CNSC Guidance G-320 states that demonstrating long-term safety should be complemented by various additional arguments based on [10-3]:

1. Appropriate selection and application of assessment strategies.
2. Demonstration of system robustness.
3. Any other evidence that is available to provide confidence in the long-term safety of radioactive waste management.

The method of compliance with the NSDF safety objective and provision of the additional arguments is summarized in Table 10-1.

Table 10-1 Performance Assessment vs. IAEA SSR-5 and CNSC Guidance G-320

Regulatory Guidance	Performance Assessment
Site, design, construct, operate, and close a disposal facility so that protection after its closure is optimized, social and economic factors being taken into account [10-2].	Near Surface Disposal Facility Siting, design, construction and operations are described in Sections 3, 4 and 5. The conclusions, as summarized above, show that the site is well understood, that the proposed design provides defense in depth via multiple containment barriers and that the environmental setting is appropriate for the type of waste and facility being considered.
A reasonable assurance also has to be provided that doses and risks to members of the public in the long-term, will not exceed the dose limit for members of the public and other risk constraints" [10-2].	Assessment findings for long-term performance are described in Section 8. Predicted doses for respective scenarios do not exceed the dose limit for members of the public and the dose constraint for Human Intrusion.
Appropriate selection and application of assessment strategies [10-3].	The assessment strategy is to provide scoping and bounding analysis, as described in Section 1.4. The strategy was implemented by selecting bounding, conservative scenarios and making conservative assumptions underpinning all analysis.
Demonstration of system robustness [10-3].	System robustness is demonstrated through a combination of: • Design, which provides multiple barriers (see Section 5). • Analysis, which demonstrated that radiological consequence to members of the public, would be acceptable, even in the unlikely event of complete loss of Institutional Control and multiple failures of defensive barriers (see Section 8).
Any other evidence that is available to provide confidence in the long-term safety of radioactive waste management [10-3].	Section 8.7 provides a natural analogue for performance over very long timescales.

Based on the above information presented in the PA, the overall conclusion is that the NSDF will satisfy the objectives of protecting human health and the environment and that there are reasonable assurances that it will provide for the safe long-term management of radioactive waste.

10.7 References

[10-1] Golder Associates. *Groundwater Flow Modelling of the Near Surface Disposal Facility (60% Design) – Draft Report.* 1547525. 2017 February.

[10-2] IAEA, *Disposal of Radioactive Waste* SSR-5, 201.

[10-3] CNSC, *Regulatory Guide G-320, Assessing the Long-Term Safety of Radioactive Waste Management*, 2006 December.

11. APPENDIX A - FEATURES, EVENTS AND PROCESSES

Table 11-1 Events with Potential Radiological Consequences – External Events

FEP # and Title	FEP Description	Relevant Scenario(s)	How is FEP addressed
2. Assessment Basis			
0.01 Impacts of Concern	The long-term human health and environmental effects or risks that may arise from the disposed wastes and repository. These FEP include human health or environmental effects of concern in an assessment what effect and to whom/what), and human health or environmental effects ruled to be of no concern.	All post-closure scenarios	Radiological doses to humans and environmental effects will be considered for each scenario.
0.03 Timescales of Concern	Timescales of concern are the time periods over which the disposed wastes and repository may present some significant human health or environmental hazard.	All post-closure scenarios	All assessments capture peak exposures under each scenario.
0.03 Spatial Domain	The spatial domain of concern is the domain over which the disposed wastes and repository may present some significant human health or environmental hazard.	All post-closure scenarios	All assessments consider domain over which potential radiological impacts on humans and ecology are plausible, either via atmospheric dispersion or ground-surface water flow.
0.04 Repository Assumptions	Repository assumptions are the assumptions that are made in the assessment about the construction, operation, closure, and administration of the repository.	All post-closure scenarios	All assumptions are specified, justified and documented.
0.05 Future Human Action Assumptions	The assumptions made in the safety assessment concerning general boundary conditions for assessing future human action.	All post-closure scenarios.	Human Intrusion scenarios considered, including chronic and acute exposure.
0.06 Future Human	The future human behaviour assumptions	All post-closure	Future human habits are assumed to be

FEP # and Title	FEP Description	Relevant Scenario(s)	How is FEP addressed
	made concerning potentially exposed individuals or population groups that are considered in the safety assessment.	scenarios.	consistent with present time; however, a conservative set of habits and consumption rates considered within sensitivity analysis.
0.07 Dose Response Assumptions	Dose response assumptions are those assumptions made in a safety assessment in order to convert received dose to a measure of risk to an individual or population.	All post-closure scenarios.	Safety criteria are defined in terms of compliance with dose limits (See Section 2). Probability is considered in a qualitative manner; however conservatively defined exposure scenarios are assumed to have occurred. As such, it is not necessary to convert received dose to a measure of risk for post-closure analysis.
0.08 Assessment Purpose	The assessment purpose is the purpose for which the safety assessment is being undertaken.	All post-closure scenarios.	The purpose is to demonstrate long-term safety of the NSDF, as described in Section 1.2.
0.09 Regulatory Requirements and Exclusions	Regulatory requirements and exclusions are the specific terms or conditions in the national regulations or guidance relating to repository post-closure safety assessment.	All post-closure scenarios.	Regulatory requirements and guidance pertaining to the NSDF post-closure safety assessment, as described in Section 1.4.
0.10 Model and Data Issues.	Model and data issues are general (i.e. methodological) issues affecting the safety assessment modelling process and use of data.	All post-closure scenarios.	The analysis includes consideration and documentation of model and data issues, such as treatment of uncertainty, data availability, method of handling site data, application of conservatism, and modelling simplifications and assumptions.
1.1 Repository Issues			
1.1.01 Site Investigation	FEPs related to the investigations that are carried out at a potential repository site in order to characterize the site both prior to repository excavation and during construction and operation.	All post-closure scenarios	The NSDF site and surrounding areas, including geosphere and surface water, have been extensively characterized, as described in Section 3.
1.1.02 Excavation/Construction	Factors related to excavation and construction activities at the NSDF Site.	All post-closure scenarios	It is assumed that construction activities will be implemented in accordance with the final design and appropriate quality requirements so that after closure the facility will perform

FEP # and Title	FEP Description	Relevant Scenario(s)	How is FEP addressed
			as designed.
1.1.03 Emplacement of Wastes and Backfilling	The methodology employed for the emplacement of wastes and backfill materials in the repository.	All post-closure scenarios	It is assumed that emplacement and backfilling activities will be implemented in accordance with the final design and appropriate quality requirements so that after closure the facility will perform as designed.
1.1.04 Repository Closure	Factors related to the cessation of waste emplacement operations at the NSDF and the backfilling and closure of the facility.	All post-closure scenarios	It is assumed that closure activities will be implemented in accordance with the final design and appropriate quality requirements so that after closure the facility will perform as designed.
1.1.05 Repository Records and Markers	Features, Events and Processes related to the retention of records of the content and nature of a repository after closure and also the placing of permanent markers at or near the site.	All post-closure scenarios, particularly human intrusion	The existence of NSDF records and markers will affect the safety of the NSDF, particularly with respect to reducing probability of inadvertent human intrusion scenarios. Two permanent granite markers will be installed after closure. The markers will be 900 mm by 900 mm square and vary from 750 mm to 300 mm in height and will be placed on a 1.5 m by 1.5 m by 0.5 m high concrete base. Each marker will show the name of the facility, date of closure, and waste capacity of the mound in cubic meters. One marker will be placed near the north entrance to the ECM on East Mattawa Road. The other will be placed at the centroid of the ECM. These markers will be placed after final closure of the mound.
1.1.06 Waste Allocation	Features, Events and Processes related to the choices on allocation of wastes to the repository, including waste type(s) and amount(s).	All post-closure scenarios	Waste acceptance criteria will define the waste allocation limits. Waste inventory was determined to ensure that long-term safety can be assured, given NSDF design and siting characteristics. Further information is

FEP # and Title	FEP Description	Relevant Scenario(s)	How is FEP addressed
			provided in Section 4.
1.1.07 Repository Design	Features, Events and Processes related to the design of the repository including both the safety concept (i.e. the general features of design and how they are expected to lead to a satisfactory performance), and the more detailed engineering specification for excavation, construction and operation.	All post-closure scenarios	Key design features, including engineered cover, backfill and base liner (Section 6) are incorporated in the analysis.
1.1.08 Quality Assurance	Features, Events and Processes related to quality assurance and control procedures and tests during the design, construction and operation of the repository, as well as the manufacture of the waste forms, containers and engineered features.	All post-closure scenarios	NSDF design and construction activities are subject to requirements of CNL procedures and project specific quality assurance plans [8-4]
1.1.09 Scheduling and Planning	Features, Events and Processes related to the sequence of events and activities occurring during repository excavation, construction, waste emplacement and closure (sealing).	All post-closure scenarios	In the context of post-closure, this impacts the period of active and passive institutional control (Section 1.7.4).
1.1.10 Repository Administrative Controls	Features, Events and Processes related to measures to control events at or around the repository site both during the operational period and after closure.	All post-closure scenarios	Institutional controls will be maintained for 300 years after closure of ECM. Human intrusion can occur only after the end of institutional control. Throughout the period of institutional control the ECM cover and base liner function as designed and any damage due to environmental factors will be mitigated.
1.1.11 Repository Monitoring	Features, Events and Processes related to any monitoring that is carried out during operations or following closure of sections of, or the total, repository. This includes monitoring for operational safety and also monitoring of parameters related to the	All post-closure scenarios	Monitoring will be carried out after closure of ECM for as long as it is necessary to demonstrate that the final cover and other containment features are performing their function in accordance with design, safety and environmental requirements.

FEP # and Title	FEP Description	Relevant Scenario(s)	How is FEP addressed
	long-term safety and performance.		
1.1.12 Accidents and Unplanned Events	Features, Events and Processes related to accidents and unplanned events during excavation, construction, waste emplacement, and closure which might have an impact on long-term performance or safety.	All post-closure scenarios	Accidents or unplanned events relating to construction, operations and closure will be analyzed in the Safety Analysis Report. Any potential impacts on long-term performance after closure will be detected in the course of monitoring, which will take place during Institutional Control. If any deficiencies were to be detected, these will be mitigated prior to the end of the Active Institutional Control period.
1.2.03 Seismicity	Features, Events and Processes related to seismic events and also the potential for seismic events. A seismic event is caused by rapid relative movements within the Earth's crust usually along existing faults or geological interfaces. The accompanying release of energy may result in ground movement and/or rupture (e.g. earthquakes).	Disruptive events	Site specific seismic surveys were conducted in 2016 [8-22] and probabilistic Seismic Hazard Analysis developed seismic hazard curves [8-17]. Seismic analysis demonstrated that the ECM containment design features will continue to perform their function after a 1 in 10,000 years seismic event [8-23]. Any potential damage resulting from a beyond design basis event occurring during the period of Institutional Control would be remediated. The impact of a beyond design basis earthquake occurring after the end of Institutional Control is discussed in Section 8.6.3.
1.2.10 Hydrological/Hydrogeological Response to Geological Changes	Features, Events and Processes related to groundwater flow and pressures arising from large-scale geological changes. These could include changes of hydrological boundary conditions due to glaciation, effects of erosion on topography, and changes of hydraulic properties of geological units due to changes in rock stress or fault movements.	All post-closure scenarios	Large-scale geological changes taking place over very long periods of time may have a significant impact on groundwater flow, including on flow direction and velocity. A number of sensitivity cases, varying hydrogeological properties have been considered in the groundwater flow modelling report [8-24], indicating little impact on contaminant transport times.

FEP # and Title	FEP Description	Relevant Scenario(s)	How is FEP addressed
			While there is uncertainty due to large-scale hydrogeological changes that may take place over hundreds or thousands of years, travel times are not likely to be less than those considered under the Bathtub overflow scenario (See Section 8.5.2.2). Even more significant changes, including site erosion, may occur as a result of glaciation. This is addressed in Sections 8.6.2 and 8.7.
1.3.01 Global Climate Change	Features, Events and Processes related to the possible future, and evidence for past, long-term change of global climate. This is distinct from resulting changes that may occur at specific locations according to their regional setting and also climate fluctuations, (FEP# 1.3.02).	All post-closure scenarios	As for FEP# 1.2.10, sensitivity of groundwater transport to changing recharge and other factors have been analyzed and shown to be minor [8-24]. Accelerated erosion would result in failure of the engineered cover, which is conservatively assumed to occur immediately after the end of institutional control under the Normal Evolution scenarios. In any case, the resulting increase in leaching and any possible reduction in travel times would be bounded by the Bathtub overflow scenario considered in Section 8.5.2.2.
1.3.02 Regional and Local Climate Change	Features, Events and Processes related to the possible future changes, and evidence for past changes, of climate at a repository site. This is likely to occur in response to global climate change, but the changes will be specific to situation, and may include shorter term fluctuations, (FEP# 1.3.01).	All post-closure scenarios	Same as for FEP# 1.3.01
1.3.05 Local Glacial and Ice Sheet Effects	Features, Events and Processes related to the effects of glaciers and ice sheets within the region of a repository (e.g. changes in the geomorphology, erosion, melt water, and hydraulic effects). This is distinct from	All post-closure scenarios	Potential consequences of glaciation are considered in Sections 8.6.2 and 8.7.

FEP # and Title	FEP Description	Relevant Scenario(s)	How is FEP addressed
	the effect of large ice masses on global and regional climate, (FEP# 1.3.01, and FEP #1.3.02).		
1.3.07 Hydrological/Hydrogeological Response to	Features, Events and Processes related to changes in hydrology and hydrogeology (e.g. recharge, sediment load and seasonality), in response to climate change in a region.	All post-closure scenarios	Same as for FEP# 1.2.10
1.3.08 Ecological Response to Climate Changes	Features, Events and Processes related to changes in ecology (e.g. vegetation, plant and animal populations), in response to climate change in a region.	All post-closure scenarios	While climate change may influence the ecology of the NSDF site, Ecological Risk Assessment considered potential impacts on a wide variety of species at every trophic level (Section 8.3).
1.3.09 Human Response to Climate Changes	Features, Events and Processes related to changes in human behaviour (e.g. habits, diet, size of communities), in response to climate change in a region.	All post-closure scenarios	Chronic exposure Human Intrusion scenario conservatively assumes that all consumption by a resident staying at the ECM site is sourced from local foodstuffs (Section 8.6.1).
1.4 Future Human Action			
1.4.01. Human Influence on Climate	Features, Events and Processes related to human activities that could affect the change of climate either globally or in a region (i.e. greenhouse effect, deforestation).		Same as for FEP# 1.3.01
1.4.02 Motivation and Knowledge Issues (inadvertent/deliberate human action)	Features, Events and Processes related to the degree of knowledge of the existence, location and/or nature of the repository. Also, reasoning for deliberate interference with or intrusion into a repository after closure, with complete or incomplete knowledge.	Human Intrusion	Inadvertent intrusion, resulting from loss of knowledge, is addressed in Section 8.6.1. Deliberate intrusion would be undertaken with knowledge of associated hazardous. Deliberate malicious interference is not covered by the scope of this assessment.
1.4.04 Drilling Activities (human intrusion)	Features, Events and Processes related to any type of drilling activity in the vicinity of the repository. These may be taken with or without knowledge of the repository (see	Human Intrusion.	Same as for FEP# 1.4.02

FEP # and Title	FEP Description	Relevant Scenario(s)	How is FEP addressed
	FEP# 1.4.02).		
1.4.06 Surface Environment, Human Activities	Features, Events and Processes related to any type of human activities that may be carried out in the surface environment that can potentially affect the performance of the engineered and/or natural (geological) barriers, or the exposure pathways.	Human Intrusion	During the institutional control period, any surface activities at the NSDF would be undertaken with knowledge of the associated hazards. Consequences from activities carried out after the end of institutional control would be bounded by human intrusion (FEP# 1.4.02).
1.4.07 Water Management (wells, reservoirs, dams)	Features, Events and Processes related to groundwater and surface water management including water extraction, reservoirs, dams, and river management.	Human Intrusion	As for FEP # 1.4.06.
1.4.08 Social and Institutional Developments	Features, Events and Processes related to changes in social patterns and degree of local government, planning and regulation.	All scenarios	Scenarios relating to loss of institutional control and human intrusion are discussed in FEP# 1.4.02. Other developments, including demographic changes, changes in land use and regulatory requirements are bounded by the level of conservatism considered under Normal Evolution scenarios 8.3.
1.4.12 Site Development	Features, Events and Processes related to any type of human activities during site development that can potentially affect the performance of the engineered and/or natural (geological) barriers, or the exposure pathways.	Human Intrusion	Prior to the end of institutional control, all site developments will account for the presence of NSDF and ensure that there is no impact on safety and environmental performance. Following the end of institutional control, on-site activities may interfere with the performance of ECM – assuming there is loss of knowledge. Human Intrusion scenarios are considered in Section 8.6.1.
1.4.14 Pollution	Features, Events and Processes related to any type of human activities associated with pollution that can potentially affect the performance of the engineered and/or natural (geological) barriers, or the	All post-closure scenarios.	Although unlikely to have a major effect, pollution (e.g., acid rain, soil pollution, groundwater pollution) could impact the chemical composition of groundwater and sorption coefficient. Sensitivity to potential

FEP # and Title	FEP Description	Relevant Scenario(s)	How is FEP addressed
	exposure pathways.		changes is considered in Section 8.8.1.3.
2.1.01 Inventory, Radionuclide and other Material	Features, Events and Processes related to the total content of the repository of a given type of material, substance, element, individual radionuclides, total radioactivity or inventory of hazardous substances.	All post-closure scenarios.	Radionuclide inventory has been defined in Section 4, based on conservative estimates. The Waste Acceptance Criteria and Quality Control programs will ensure that the estimated inventory is indeed bounding. Migration of hazardous constituents is evaluated elsewhere.
2.1.02 Waste Form Materials and Characteristics	Features, Events and Processes related to the waste form materials and characteristics. The waste form will usually be conditioned prior to disposal (e.g. by solidification and inclusion of grout materials). The waste characteristics will evolve due to various processes that will be affected by the physical and chemical conditions of the repository environment. Processes that are relevant specifically as waste degradation processes, as compared to general evolution of the near field, are included in this FEP.	All post-closure scenarios.	A conservative assumption was made that no credit should be taken for encapsulation of waste in the grout or packaging after the end of institutional control. Up to that point post-closure assessments assumed that there is no leaching, which is another conservative assumption, maximizing the inventory available for leaching after closure.
2.1.03 Container Materials and Characteristics	Features, Events and Processes related to the physical, chemical, biological characteristics of the container at the time of disposal and also as they may evolve in the repository, including FEP which are relevant specifically as container degradation/failure processes.	All scenarios	As for FEP # 2.1.02
2.1.04 Backfill Materials and Characteristics	Features, Events and Processes related to the physical, chemical, biological characteristics of the backfill at the time of disposal and also as they may evolve in the repository, including FEP which are relevant specifically as buffer/backfill	All scenarios	The backfill material is credited to ensure stability of the ECM, based on the design calculations [8-23]. No credit is taken for encapsulation of the waste into a cement or grout matrix and/or lowering pH to prevent leaching of contaminants after the end of

FEP # and Title	FEP Description	Relevant Scenario(s)	How is FEP addressed
	degradation processes.		institutional control.
2.1.05 Engineered Barriers System, Characteristics and Degradation Process	Features, Events and Processes related to the design, physical, chemical, hydraulic etc. characteristics of the engineered barriers system at the time of sealing and also as they may evolve in the repository.	All scenarios	A set of conservative assumptions is considered, assuming failure of the engineered cover and/or base liner after the end of institutional control (see Section 8.3).
2.1.06 Other Engineered Features Materials and Characteristics	Features, Events and Processes related to the physical, chemical, biological characteristics of the engineered features (other than containers, buffer/backfill, and seals) at the time of disposal and also as they may evolve in the repository, including FEP which are relevant specifically as degradation processes acting on the engineered features.	All scenarios	Other NSDF engineered features include the perimeter berm, gas venting system, and leachate collection system. Complete or partial failure of these systems is considered in the post-closure assessment.
2.1.07 Mechanical Processes and Conditions (in wastes and Engineered Barrier System)	Features, Events and Processes related to the mechanical processes that affect the wastes, containers, seals, Engineered Barrier System, and other engineered features, and the overall mechanical evolution of near field with time. This includes the effects of hydraulic and mechanical loads imposed on wastes, containers and repository components by the surrounding geology.	All scenarios	The waste packages, backfill, and ECM features will be subject to mechanical loads following closure. This could lead to mechanical failure of packages, movement of wastes, cover failure, and failure of gas venting or leachate collection system components. No credit is taken for engineered barriers following the end of Institutional Control
2.1.08 Hydraulic/Hydrogeological Processes and Conditions (in Wastes and Engineered Barrier System)	Features, Events and Processes related to the hydraulic/hydrogeological processes that affect the wastes, containers, seals and other engineered features, and the overall hydraulic/hydrogeological evolution of near field with time. This includes the effects of hydraulic/hydrogeological influences on wastes, containers and repository	All scenarios	Hydraulic and hydrogeological processes that may affect the NSDF include: infiltration and movement of rain and groundwater, saturation, and desaturation. These processes may impact the mobility of contaminants from the NSDF and may alter exposure pathways. Conceptual model described in Section 8.3 represents conservative interpretation of potential

FEP # and Title	FEP Description	Relevant Scenario(s)	How is FEP addressed
	components by the surrounding geology.		hydrogeological and hydraulic processes.
2.1.09 Chemical/Geochemical Processes and Conditions (in wastes and Engineered Barrier System)	Features, Events and Processes related to the chemical/geochemical processes that affect the wastes, containers, seals, Engineered Barrier System, and other engineered features, and the overall chemical/geochemical evolution of near field with time. This includes the effects of chemical/geochemical influences on wastes, containers and repository components by the surrounding geology.	All scenarios	Chemical processes may influence the degradation of materials within the NSDF and impact radionuclide mobility. It is assumed that after the end of institutional control radionuclides are readily available for desorption, a conservative set of sorption coefficients is used and no credit is taken for waste form.
2.1.10 Biological/Biochemical Processes and Conditions (in wastes and Engineered Barrier System)	Features, Events and Processes related to the biological/biochemical processes that affect the wastes, containers, seals, Engineered Barrier System, and other engineered features, and the overall biological/biochemical evolution of near field with time. This includes the effects of biological/biochemical influences on wastes, containers and repository components by the surrounding geology.	All scenarios	As for FEP # 2.1.09
2.1.12 Gas sources and Effects (in wastes and Engineered Barrier System)	Features, Events and Processes within and around the wastes, containers (packaging) and engineered features (i.e. Engineered Barrier System) resulting in the generation of gases and their subsequent effects on the repository system.	All scenarios	Gases may be generated in the NSDF from degradation or corrosion effects, decomposition of wastes, chemical interactions, and radiation effects. Radioactive decay of some wastes may produce gaseous isotopes. Radon gas will be produced from the decay of uranium, thorium, and radium. Doses due to gaseous radionuclides are evaluated as part of considered post-closure scenarios.
2.1.14 Nuclear Criticality	Features, Events and Processes related to the possibility and effects of spontaneous nuclear fission chain reactions within the	All scenarios	A separate criticality analysis has been conducted to demonstrate Criticality Safety of ECM (see Section 7.5).

FEP # and Title	FEP Description	Relevant Scenario(s)	How is FEP addressed
	repository.		
2.2.04 Discontinuities, Large Scale (in geosphere).	Features, Events and Processes related to the properties and characteristics of discontinuities in and between the host rock and geological units, including faults, shear zones, intrusive dykes, and interfaces between different rock types.	All scenarios	The CRL site is located along the Ottawa-Bonnechere Graben, within the Grenville Structural Province of the Canadian Shield. The Grenville Structural Province features large and small scale faults. It is plausible that a small fraction of leachate may be delivered to the Ottawa River via fracture flow. However, the fast and direct pathway considered for the Bathtub scenario bounds consequences resulting from such releases due to higher velocities and radionuclide flux associated with this pathway (see Section 8.5.2.2).
2.2.05 Contaminant Transport Path Characteristics (in geosphere)	Features, Events and Processes related to the properties and characteristics of smaller discontinuities and features within the host rock and other geological units that are expected to be the main paths for contaminant transport through the geosphere, as they may evolve both before and after repository closure.	All scenarios	Local geology impacts groundwater flows in the geosphere (see Section 3.3). Properties of various geological units have been used to formulate groundwater transport model, which formed the basis geosphere modelling (Section 8.3).
2.2.07 Hydraulic/Hydrogeological Processes and Conditions (in geosphere)	Features, Events and Processes related to the hydraulic and hydrogeological processes that affect the host rock and other rock units, and the overall evolution of conditions with time. This includes the effects of changes in condition (e.g. hydraulic head), due to the excavation, construction and long-term presence of the repository.	All scenarios	Local hydrogeology defines groundwater flows at the geosphere (see Section 3.4). Local hydrogeology has been used to formulate groundwater transport model, which formed the basis geosphere modelling (Section 8.3).
2.2.08 Chemical/Geochemical Processes and Conditions (in geosphere)	Features, Events and Processes related to the chemical and geochemical processes that affect the host rock and other rock	All scenarios	Site specific distribution coefficients have been used for analysis of radionuclide transport in the groundwater (See Section

FEP # and Title	FEP Description	Relevant Scenario(s)	How is FEP addressed
	units, and the overall evolution of conditions with time. This includes the effects of changes in condition (e.g. pH), due to the excavation, construction and long-term presence of the repository.		3.4). These reflect both present conditions and potential impact of waste presence due to influence of leachate from Waste Management Areas.
2.2.11 Gas Sources and Effects (in geosphere)	Features, Events and Processes related to natural gas sources and production of gas within the geosphere, and also the effect of natural and repository produced gas on the geosphere, including the transport of bulk gases and the overall evolution of conditions with time.	All scenarios	An assessment of consequences from gaseous emissions is included for both normal evolution and disruptive scenarios.
2.2.12 Undetected Features (in geosphere)	Features, Events and Processes related to natural or man-made features within the geology that may not be detected during the site investigation.	All scenarios	Same as for FEP 2.2.04.
2.3.01 Topography and Morphology	Features, Events and Processes related to the relief and shape of the surface environment and its evolution. This FEP refers to local land form and land form changes with implications for the surface environment (e.g. plains, hills, valleys), and effects of river and glacial erosion thereon. In the long-term, such changes may occur as a response to geological changes, see FEP# 1.3.	All scenarios	The topography of the NSDF site and surrounding area is relevant to groundwater flows and surface water Management (Section 3.2). These factors also influence the locations of receptors and relevant water supplies and are represented in the analysis.
2.3.02 Soil and Sediment	Features, Events and Processes related to the characteristics of the soils and sediments and their evolution.	All Scenarios	Soil and sediment characteristics influence the mobility and transfer of contaminants in the environment. Soil characteristics additionally influence the erosion of the NSDF, rate of water infiltration, and leachate generation. Soil and sediment properties have been incorporated in the models for normal evolution and disruptive events.

FEP # and Title	FEP Description	Relevant Scenario(s)	How is FEP addressed
2.3.03 Near Surface Aquifers and Water-Bearing Features	Features, Events and Processes related to the characteristics of aquifers and waterbearing features within a few metres of the land surface and their evolution.	All Scenarios	Near surface aquifers are the main conduits for contaminant transport after the end of institutional control (Section 3.4), and are represented in the conceptual model and analysis (Section 8.3).
2.3.04 Lakes, Rivers, Streams, and Springs	Features, Events and Processes related to the characteristics of terrestrial surface water bodies and their evolution.	All Scenarios	The NSDF is located in the Perch Lake basin. After the end of institutional control in the event of engineering barriers failing, contaminant transport will direct radionuclide flux into the Perch Creek, which in turn flows into the Ottawa River (see Section 8.3).
2.3.07 Atmosphere	Features, Events and Processes related to the characteristics of the atmosphere, including capacity for transport, and their evolution.	All Scenarios	Atmospheric exposure pathways are considered for emissions of gaseous radionuclides for both Human Intrusion (8.6.1) and Normal Evolution scenarios (8.3).
2.3.08 Vegetation	Features, Events and Processes related to the characteristics of terrestrial and aquatic vegetation both as individual plants and in mass, and their evolution.	All Scenarios	Vegetation is a pathway for humans and non-human biota to become exposed to contaminants associated with the NSDF. Airborne and liquid effluent from the NSDF may enter vegetation, which may then be consumed by other receptors. This is considered within the biosphere model for both Human Intrusion (8.6.1) and Normal Evolution scenarios (8.3).
2.3.09 Animal Populations	Features, Events and Processes related to the characteristics of the terrestrial and aquatic animals both as individual animals and as populations, and their evolution.	All Scenarios	As for FEP 2.3.08.
2.3.10 Weather and Climate	Features, Events and Processes related to the characteristics of weather and climate, and their evolution.	All Scenarios	Weather and climate influence the transport of NSDF contaminants in environmental media and are represented in the analysis presented in both Human Intrusion (8.6.1) and Normal Evolution scenarios (8.3).

FEP # and Title	FEP Description	Relevant Scenario(s)	How is FEP addressed
			Weather and climate characteristics additionally influence the degradation of the NSDF as they may affect the erosion of the ECM cover. This is represented through conservatively assuming that the cover will fail following the end of institutional control.
2.3.11 Hydrological Regime and Water Balance (near-surface)	Features, Events and Processes related to near-surface hydrology at a catchment's scale and also soil water balance, and their evolution.	All scenarios	As for FEP 2.2.07.
2.3.12 Erosion and Deposition	Features, Events and Processes related to all the erosion and deposition processes that operate in the surface environment, and their evolution.	All scenarios	Erosion of the NSDF cover may result in contaminants being released to the environment. This is represented through conservatively assuming that the cover will fail following the end of institutional control.
2.3.13 Ecological/Biological/Microbial Systems	Features, Events and Processes related to living organisms and relations between populations of animals, plants and microbes and their evolution.	All scenarios	Ecological system characteristics influence the transport of contaminants in the environment. They may impact the processes of degradation within the ECM. It has been assumed that contaminants become available for desorption and leaching following the end of institutional control. Ecological systems may also impact transfer of radionuclides in the ecosystem and to receptors. See FEP 2.3.08 and 2.3.09.
2.3.14 Animals/Plants Intrusion	Features, Events and Processes related to animal and plant intrusion.	All scenarios	Animal and plant intrusion into the NSDF may cause contaminants to be released. Uptake of contaminants by intruding animals and plants represent a pathway for human and non-human receptor exposure to NSDF contaminants. It has been conservatively

FEP # and Title	FEP Description	Relevant Scenario(s)	How is FEP addressed
			assumed that the engineered cover will fail immediately following the end of institutional control.
2.4.01 Human Characteristics (physiology, metabolism)	Features, Events and Processes related to characteristics (e.g. physiology, metabolism), of individual humans. Physiology refers to body and organ form and function. Metabolism refers to the chemical and biochemical reactions which occur within an organism or part of an organism, in connection with the production and use of energy.	All scenarios	Current ICRP exposure models were considered for physiological characteristics. Current set of human habits formed the basis of Normal Evolution scenarios; however, a more conservative set of assumptions was also considered to evaluate sensitivity to variation in human habits (see Section 8.8).
2.4.02 Age, Children, Infants and Other Variations	Features, Events and Processes related to considerations of variability, in individual humans, of physiology, metabolism and habits.	All Scenarios	Human receptor characteristics related to age influence exposure to contaminants associated with the NSDF. The models used age categories of 0 to <5 (infant), 5 to <15 (child), and 15 and older (adult), as specified in CSA N288.1-14, including specified characteristics.
2.4.03 Diet and Fluid Intake	Features, Events and Processes related to intake of food and water by individual humans, and the compositions and origin of intake	All Scenarios	See FEP 2.4.01.
2.4.04 Habits (non-diet related behaviour)	Features, Events and Processes related to non-diet related behaviour of individual humans, including time spent in various environments, pursuit of activities and uses of materials.	All Scenarios	See FEP 2.4.01.
2.4.05 Community Characteristics	Features, Events and Processes related to characteristics, behaviour and lifestyle of groups of humans that might be considered as target groups in an assessment.	All Scenarios	See FEP 2.4.01.
2.4.07 Dwellings	Features, Events and Processes related to	All Scenarios	See FEP 2.4.01. Occupancy factors are based

FEP # and Title	FEP Description	Relevant Scenario(s)	How is FEP addressed
	houses or other structures or shelter in which humans spend time.		on CSA N288.1-14.
2.4.08 Natural/Semi-Natural Land and Water Use	Features, Events and Processes related to use of natural or seminatural tracts of land and water such as forest, bush and lakes.	All Scenarios	See FEP 2.4.01.
2.4.09 Rural and Agricultural Land and Water Use (incl. fisheries)	Features, Events and Processes related to use of permanently or sporadically agriculturally managed land and managed fisheries.	All Scenarios	See FEP 2.4.01.
2.4.10 Urban and Industrial Land and Water Use	Features, Events and Processes related to urban and industrial developments, including transport, and their effects on hydrology and potential contaminant pathways.	All Scenarios	See FEP 2.4.01.
2.4.11 Leisure and Other Uses of Environment	Features, Events and Processes related to leisure activities, the effects on the surface environment and implications for contaminant exposure pathways.	All Scenarios	See FEP 2.4.01.
3.1 Contaminant Characteristics			
3.1.01 Radioactive Decay and In-growth	Radioactivity is the spontaneous disintegration of an unstable atomic nucleus resulting in the emission of subatomic particles. Radioactive isotopes are known as radionuclides. Where a parent radionuclide decays to a daughter nuclide so that the population of the daughter nuclide increases, this is known as ingrowth.	All Scenarios	Radioactive decay and ingrowth are considered for all scenarios.
3.1.02 Chemical/Organic Toxin Stability	Features, Events and Processes related to chemical stability of non-radiological (chemical) contaminants.	Not considered in Performance Assessment	Impacts relating to chemical contaminants are considered in the EIS.
i. Inorganic Solids/Solutes	Features, Events and Processes related to the characteristics of inorganic solids/solutes that may be considered.	All Scenarios	Inorganic radiological contaminants are considered in all scenarios.

FEP # and Title	FEP Description	Relevant Scenario(s)	How is FEP addressed
i. Volatiles and Potential for Volatility	Features, Events and Processes related to the characteristics of radionuclide and chemical contaminants that are volatile or have the potential for volatility in the repository or the environment.	All Scenarios	The NSDF inventory includes volatile radionuclides, such as C-14 and Tritium. Radon gas will be generated as a result of ingrowth. Doses due to emissions of these radionuclides are considered in the analysis.
3.1.05 Organics and Potential for Organic Forms	Features, Events and Processes related to the characteristics of radionuclide and chemical contaminants that are organic or have the potential to form organics in the repository or the environment.	All Scenarios	Transport of organic contaminants is considered in the EIS.
3.1.06 Noble Gases	Features, Events and Processes related to the characteristics of noble gases.	All Scenarios	Doses due to Radon and other noble gases are considered in the analysis.
3.2 Contaminant Release/Migration Factors			
3.2.01 Dissolution, Precipitation and Crystallization-Contaminant	Features, Events and Processes related to the dissolution, precipitation and crystallization of radiological and non-radiological (chemical) contaminants under repository or environmental conditions.	All Scenarios	Post-closure analysis uses sorption/desorption and solubility model, as implemented in the RESRAD-OFFSIDE software package.
3.2.02 Speciation and Solubility-Contaminant	Features, Events and Processes related to the chemical speciation and solubility of radiological and non-radiological (chemical) contaminants in repository or environmental conditions.	All Scenarios	As FEP 3.2.01.
3.2.03 Sorption/Desorption Processes-Contaminant	Features, Events and Processes related to sorption/desorption of radiological and non-radiological (chemical) contaminants in repository or environmental conditions.	All Scenarios	As FEP 3.2.01.
3.2.04 Colloids-Contaminant Interactions and Transport	Features, Events and Processes related to the transport of colloids and interaction of radiological and non-radiological (chemical) contaminants with colloids in repository or environmental conditions.	All Scenarios	As FEP 3.2.01.
3.2.06	Features, Events and Processes related to	All Scenarios	As FEP 3.2.01 and FEP 2.3.13.

FEP # and Title	FEP Description	Relevant Scenario(s)	How is FEP addressed
Microbial/Biological/Plant-Mediated Processes-Contaminant	the modification of contaminant speciation or properties due to microbial/biological/plant activity.		
3.2.07 Water-Mediated Transport of Contaminants	Features, Events and Processes related to the modification of contaminant speciation or properties due to microbial/biological/plant activity.	All Scenarios	Some contaminants will be released from the NSDF in waterborne effluent. Watermediated transport will influence the dispersion of contaminants in the environment and exposure pathways for humans and non-human biota. Water transport processes are represented in the analysis (Sections 8.3 and 8.6).
3.2.08. Solid-Mediated Transport of Contaminants	Features, Events and Processes related to transport of radiological and non-radiological (chemical) contaminants in solid phase, for example large-scale movements of sediments, landslide, solifluction, and volcanic activity.	All scenarios	Transport of solids, such as soil and sediment is considered in the analysis (Sections 8.3 and 8.6).
3.2.09 Gas-Mediated Transport of contaminants	Features, Events and Processes related to transport of radiological and non-radiological (chemical) contaminants in gas or vapour phase or as fine particulate or aerosol in gas or vapour.	All Scenarios	Gaseous contaminants may be generated in the NSDF and they could be released in the vapour phase, e.g. in the case of Tritium. Doses due to gas-mediated transport of contaminants are evaluated (see FEP 2.3.07)
3.2.10 Atmospheric Transport of Contaminants	Features, Events and Processes related to transport of radiological and non-radiological (chemical) contaminants in the air as gas, vapour, fine particulate, or aerosol.	All Scenarios	See FEPs 2.3.07.
3.2.11 Animal, Plant and Microbe Mediated Transport of Contaminants	Features, Events and Processes related to transport of radiological and non-radiological (chemical) contaminants as a result of animal, plant and microbial activity.	All Scenarios	See FEPs 2.3.14.
3.2.12 Human-Action Mediated Transport of Contaminants	Features, Events and Processes related to transport of radiological and non-	Human Intrusion	Human Intrusion scenarios representing human-action mediated transport of

FEP # and Title	FEP Description	Relevant Scenario(s)	How is FEP addressed
	radiological (chemical) contaminants as a direct result of human actions.		radionuclides are described in Section 8.6.1.
3.2.13 Food Chains and Uptake of Contaminants	Features, Events and Processes related to incorporation of radiological and non-radiological (chemical) contaminants into plant or animal species that are part of the possible eventual food chain to humans.	All Scenarios	The transport of contaminants through the food chain is potential exposure pathway for humans and non-human biota. All post-closure scenarios consider radionuclide uptake through foodchain.
3.3 Exposure Factors			
3.3.01 Contaminant Concentrations in Drinking Water, Foodstuffs and Drugs	Features, Events and Processes related to the presence of radiological and non-radiological (chemical) contaminants in drinking water, foodstuffs or drugs that may be consumed by humans.	All Scenarios	See FEP 3.2.13.
3.3.02 Contaminant Concentrations in Environmental Media	Features, Events and Processes related to the presence of radiological and non-radiological (chemical) contaminants in environmental media other than drinking water, foodstuffs or drugs.	All Scenarios	Contaminated environmental media (e.g., air, soil) are potential exposure pathways that could result in radiological dose or chemical exposure for human and nonhuman biota. Exposure due to presence and transfer of radionuclides in environmental media is analyzed in all considered scenarios.
3.3.03 Contaminant Concentrations in Non-Food Products	Features, Events and Processes related to the presence of radiological and non-radiological (chemical) contaminants in human manufactured materials or environmental materials that have special uses (e.g. clothing, building materials and peat)		Not considered. There is no suitable material for clothing, building materials and peat within ECM and in the immediate vicinity of NSDF.
3.3.04. Exposure Models	Features, Events and Processes related to the exposure of humans and non-human biota to radiological and non-radiological (chemical) contaminants.	All Scenarios	Exposure models are described in Sections 8.3 and 8.6.
3.3.05 Dosimetry	Features, Events and Processes related to the dependence between radiation or	All scenarios	Radiation dose to receptors depends on the form of exposure (e.g., ingestion, inhalation,

FEP # and Title	FEP Description	Relevant Scenario(s)	How is FEP addressed
	chemical toxicity effect, and the amount and the distribution of radiation or chemical toxins in the organs of the body.		external exposure), metabolism of the contaminant (e.g., the extent to which it is retained in specific body tissues), the duration of exposure, and energy and type of radioactive emissions. Dosimetric models are described in Sections 8.3 and 8.6.
3.3.06 Radiological Toxicity/Effects (humans/biota)	Features, Events and Processes related to the effect of radiation on humans and non-human biota	All scenarios	Radiological toxicity/effects on humans and non-human biota are analyzed as described in Sections 8.3 and 8.6.
3.3.07 Chemical Toxicity/Effects (humans/biota)	Features, Events and Processes related to the effects of non-radiological (chemical) contaminants on humans or non-human biota.		Chemical toxicity effects are considered in the EIS.
3.3.08 Radon and Radon Daughter Exposure	Features, Events and Processes related to exposure to radon and radon daughters.	All scenarios	Exposure to radon and radon daughter is relevant to the long-term performance and safety of the NSDF. This exposure is considered in the scenarios presented in Sections 8.3 and 8.6.